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RESEARCH MEMORANDUM

TEMPERATURES IN A J47-25 TURBOJET-ENGINE COMBUSTOR AND TURBINE SECTIONS DURING STEADY-STATE AND TRANSIENT OPERATION IN A SEA-LEVEL TEST STAND

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
June 3, 1955

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TEMPERATURES IN A J47-25 TURBOJET-ENGINE COMBUSTOR AND TURBINE SECTIONS DURING STEADY-STATE AND TRANSIENT OPERATION IN A SEA-LEVEL TEST STAND

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SUMMARY

In order to determine the conditions of engine operation causing the most severe thermal stresses in the hot parts of a turbojet engine, a J47-25 engine was instrumented with thermocouples and operated to obtain engine material temperatures under steady-state and transient conditions.

Temperatures measured during rated take-off conditions of nozzle guide vanes downstream of a single combustor differed on the order of 400° F depending on the relation of the blades position to the highest temperature zone of the burner. Under the same operation conditions, measured midspan temperatures in a nozzle guide vane in the highest temperature zone of a combustor wake ranged from approximately 1670° F at leading and trailing edges to 1340° F at midchord on the convex side of the blade. The maximum measured nozzle-guide-vane temperature of 1920° F at the trailing edge occurred during a rapid acceleration from idle to rated take-off speed following which the tail-pipe gas temperature exceeded maximum allowable temperature by 125° F.

The highest spanwise temperature zone of the turbine blade during steady-state operation at rated take-off conditions was located $2\frac{1}{4}$ inches from the base platform (60-percent span). A chordwise temperature profile measured in this zone during operation at the same conditions showed temperatures ranging from 1470° F at the leading edge to 1440° F at the trailing edge. The measured maximum turbine-blade temperature of this engine occurred during an intentional "hot start." In a typical hot start, a leading-edge temperature peak of 1860° F was reached at an engine speed of 2200 rpm. During the hot start, the blade leading edge reached a temperature 840° F higher than the midchord temperature, while the trailing edge reached a maximum of 500° F higher than midchord temperature. These maximum temperature differences

occurred 13 seconds after ignition at which time the engine speed was 1400 rpm. Steady-state turbine-wheel temperatures were measured at maximum rated take-off engine conditions. The maximum temperature measured was 1185° F in the center plane of the disk at a radius of 13.1 inches. This temperature was attained within 10 minutes after acceleration from idle to full power condition.

INTRODUCTION

In computing thermal stress and in evaluating materials or designs for use in the combustor or turbine sections of a turbojet engine, knowledge of the temperature gradients occurring in engine parts during the various types of engine operation is highly desirable. Measurements of temperatures during transient operation are necessary in order to discover the magnitude of temperature gradients that occur and the time intervals over which they take place. In order to measure some of these operating temperatures, an experimental investigation was made at the NACA Lewis laboratory using a J47-25 turbojet engine in a sea-level test stand. 3403

During steady-state operation at 7950 rpm and 1260° F tail-pipe gas temperature (rated take-off conditions for this engine), the following measurements were taken:

(a) Gas temperature in a combustor transition liner

(b) Metal temperatures of nozzle guide vanes

(c) Metal temperatures of turbine blades

Metal temperatures of the turbine wheel were measured at 7950 rpm and the maximum allowable tail-pipe gas temperature of 1275° F. During a normal start and two cycles of operation, turbine-wheel temperatures were measured at approximately 2-minute intervals. The cycles each consisted of 5 minutes at 3000 rpm, followed by 15 minutes at 7950 rpm at 1275° F tail-pipe gas temperature.

During transient operation of the engine during normal starts, hot starts, and rapid accelerations, continuous records were made of:

(a) Metal temperatures of nozzle guide vanes

(b) Metal temperatures of turbine blades

(c) Tail-pipe gas temperature

(d) Engine speed

(e) Throttle lever position

APPARATUS

A J47-25 engine was instrumented to obtain combustor-outlet gas temperatures, nozzle-guide-vane metal temperatures, and turbine-blade metal temperatures. The configurations employed to obtain these temperatures are described in the following paragraphs:

Combustor-Outlet Gas Temperature (Station 1)

In order to obtain combustor-outlet gas temperatures, three double-shielded aspirated thermocouple probes were installed in a combustor outlet (fig. 1) to make it possible to traverse the combustor outlet radially from inner shell to outer shell in the combustor transition liner. The probes were located in such a manner that the thermocouple moved along the centers of three equal areas in the cross section of the combustor-outlet area. The probe construction is shown in figure 2 and a diagram of the combustor-outlet configuration is shown in figure 3. The fuel nozzle selected for this combustor had characteristics similar to the average fuel-weight-flow characteristics of the eight fuel nozzles in the engine.

Nozzle-Diaphragm Thermocouples (Station 2)

The variation in operating temperatures of the nozzle guide vanes behind a single combustor was measured by installing a single thermocouple on each of 10 adjacent guide vanes that covered 25 percent more than the outlet area of combustor 1 as shown in figure 4. The combustor referred to, is combustor 1 at approximately 1 o'clock position looking forward and was one of the combustors that does not have spark plugs. The thermocouple beads were imbedded in the metal at midthickness, at midspan, and approximately 40-percent chord from the leading edge on the concave face of each of the 10 blades. The thermocouples were constructed of 24-gage (0.0201 diam.) chromel-alumel wire and the leads were carried through the hollow nozzle guide vanes.

To determine the chordwise temperature pattern of the nozzle guide vanes, a second nozzle diaphragm was prepared (fig. 5) by the installation of 35 thermocouples arranged in groups of seven per blade at midspan on five adjacent blades corresponding to blades 2 to 6 on figure 4. The thermocouples were made of 24-gage (0.0201 diam.) chromel-alumel wire with the bead installed in the blade metal at midthickness of each particular station on the blade. Lead wires were routed through the hollow blade with the single exception of the trailing-edge installation. Here the lead wires were enclosed in a 0.075-diameter stainless-steel conduit, which was faired into a recess cut into the trailing edge in such a manner that the original airfoil section was maintained.

Turbine-Blade Thermocouples (Station 3)

To determine the spanwise temperature profile of the airfoil section a set of three turbine blades was prepared having two thermocouples per blade located at two of the six positions along the span at midchord as shown in figure 6. A photograph of a typical instrumented blade installation is shown in figure 7. The thermocouples were made of 28-gage (0.0126 diam.) chromel-alumel wire and in each case were installed at midthickness at the particular location on the blade. Installation of thermocouples was accomplished by drilling a small hole at the desired location, locating the thermocouple bead at midthickness, and filling the hole with Number 100 Colmonoy high-temperature solder. Lead wires from the thermocouples were encased in ceramic tubing which was protected by stainless steel conduit of 0.075-inch outside diameter and 0.005-inch wall. The enclosing conduit was secured to the convex face of the blade by straps of 0.005-inch-thick Nichrome spot-welded to the blade material. At the blade base the conduit was led through an angularly drilled passage which opened to the aft end of the blade-root section. The conduit was led radially inward to the center of the turbine disk and attachment to the disk was accomplished by closely over-laying and spot-welding to the rear face of the turbine wheel a ribbon of Nichrome 1/4-inch wide and 0.005-inch thick. The lead wires were led to a slip-ring assembly on the engine accessory case through a 3/8-inch-diameter drilled hole in the turbine bolt and compressor shaft. The turbine blades were standard S-816 material.

Following the determination of the highest temperature location on the span of the blade as described later, a second set of turbine blades was instrumented to obtain the chordwise temperature profile of the airfoil at this location by installation of thermocouples at five positions along the chord as shown in figure 6. There were three blades used in this set with the thermocouples distributed among the blades as follows:

(a) Leading edge and midchord

(b) Trailing edge and midchord

(c) 25-Percent chord and 75-percent chord

The thermocouple installation technique was the same as the procedure described for the spanwise survey installation with the exception of the leading- and trailing-edge thermocouples. In these two cases, the thermocouple bead was electrical resistance welded in place in a notch ground into the blade edge, which was then filled into the original airfoil shape with the same high-temperature solder described previously. The location of these edge thermocouples was in the center of the radii defining the leading and trailing edges.

Turbine-Wheel Thermocouples (Station 3)

Thermocouples were installed in the bottoms of holes drilled from the rear face of the turbine wheel (fig. 8) to measure turbine-wheel temperatures. The lead wires from these thermocouples were protected and fastened to the rear face of the turbine wheel as shown in figure 9 and run to the slip rings using a technique identical to that described for the turbine-blade thermocouples.

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Tail-Pipe Gas Thermocouples (Station 4)

The tail-pipe gas temperature during steady-state operation was measured by averaging the readings of 14 bare-wire chromel-alumel thermocouples equally spaced around the tail pipe at station 4 immediately downstream of the engine tail cone. The thermocouple beads were located 2 inches radially inward from the wall of the tail pipe.

During the transient runs, four high-response-rate thermocouples were installed at station 4, approximately 90° apart. The bead and the first 3/32 inch of lead wire for these thermocouples was made up of 30-gage (0.010 diam.) chromel-alumel wire, which was in turn welded to 16-gage (0.051 diam.) alloy lead wire. These thermocouples were installed with the beads 2 inches radially inward from the wall of the tail pipe.

The calculated temperature-time constant of the high-response thermocouples with the engine operating at rated take-off conditions was 0.07 second, meaning that the thermocouples would indicate 62 percent of the actual surrounding gas temperature in 0.07 second (ref. 1).

Temperature-Indicating Instruments

Steady-state combustor-outlet gas temperatures and steady-state nozzle vane temperatures were read on an indicating electronic potentiometer.

Steady-state turbine-blade temperatures and tail-pipe gas temperatures and all turbine-wheel temperatures were recorded on a strip-chart recording electronic potentiometer. Transient data were recorded by a multichannel oscillograph.

Engine Instrumentation

Engine rotor speed was measured by a chronometric tachometer. No provision was made for engine thrust or fuel-flow measurement. The engine was equipped with a manually adjustable jet nozzle by means of which the tail-pipe gas temperature was regulated. All engine operation was performed with a standard engine fuel regulator installed and in normal operating condition.

PROCEDURE

The steady-state operation was performed with the engine operating at a rotor speed of 7950 rpm with a tail-pipe gas temperature of 1260° F. 3403
All temperatures measured were allowed to stabilize before any data points were read.

Combustor-Outlet Temperature

To measure combustor-outlet gas temperatures, the three double-shielded aspirated probes were installed and first located at the innermost position. The engine was started and temperature readings were made of the probe thermocouples upon attainment of equilibrium at rated conditions of 7950 rpm and 1260° F tail-pipe gas temperature. Between runs at the six subsequent positions of the probes, the engine was slowed to the 3000 rpm idle speed while the probe position was shifted manually.

In each case the representative temperature was taken to be the center point of the region of swing of the instrument during a period of approximately 1 minute of observation.

Nozzle Guide Vanes

Readings of midspan, 40-percent chord temperatures on the concave side of ten nozzle guide vanes were made on a subsequent run. After reaching equilibrium conditions, readings were made on an indicating potentiometer.

To measure the chordwise temperature profiles of nozzle guide vanes upon completion of the preceding operation, the second nozzle diaphragm having 35 thermocouples at chordwise survey locations was installed in the engine. Readings were made in the same manner as noted previously for the first nozzle diaphragm.

Turbine Blades

To obtain the spanwise temperature profile of the turbine-blade airfoil, the set of turbine blades having thermocouples at midchord and various distances from the blade base were installed and the engine was operated at rated speed and tail-pipe gas temperature. When equilibrium temperature was reached, the blade temperatures were recorded on a strip-chart recording potentiometer. The data thus obtained were analyzed to determine the highest temperature region in the blade span. This information was used in locating the thermocouples on another set of blades for determining the chordwise temperature distribution.

3403 Steady-state readings were obtained for the chordwise survey thermocouples in the manner described previously.

An additional series of runs were made at a later date with another set of instrumented blades in another engine in which spanwise temperatures were obtained corresponding to tail-pipe gas temperatures of 1235°, 1275°, and 1290° F.

Turbine-Wheel Temperature Measurements

Turbine-wheel temperatures were recorded during a normal starting sequence lasting 2 minutes followed by two cycles of operation consisting of 5 minutes at 3000 rpm and 15 minutes at 7950 rpm and 1275° F tail-pipe gas temperature. Temperature readings were made at approximate 2-minute intervals.

Transient-Temperature Measurements

For the transient-temperature measuring runs, the thermocouple voltages were fed to individual channels of a multichannel oscillograph. Suitable balancing circuits and oscillograph elements were selected to provide for the temperature ranges to be encountered.

Engine speed was recorded by an oscillograph element driven by a voltage divider across the output of a tachometer generator driven by one of the engine accessory pads.

Engine throttle-arm position was recorded by an oscillograph element actuated by the voltage derived from a potentiometer circuit wherein the potentiometer was directly linked to the throttle arm.

Normal Starts

During a normal starting test the following procedure was used:

(a) The starter was energized

(b) The rotor speed increased to approximately 600 rpm

(c) The engine throttle lever was advanced to a starting position indicated on the throttle quadrant

(d) Ignition was energized

(e) The fuel-supply valve was opened, allowing the engine fuel system to furnish fuel to the fuel nozzles

(f) Ignition occurred 3403

(g) The engine accelerated slowly to 2000 rpm

(h) The starter motor was de-energized and the acceleration continued to 3000 rpm

During steps (f) through (h) the operator observed the tail-pipe gas temperature closely and retarded the throttle lever in case of a threatened excursion of gas temperature above 1600° F which is the normal temperature limit allowed for service operation of this engine. Control of this engine during the starting cycle was purely manual with the fuel regulator operating above 3000 rpm only.

Hot Starts

During a hot start the following procedure was followed:

(a) The starter was engaged

(b) The rotor speed increased to approximately 600 rpm

(c) The engine throttle lever was advanced to a point beyond the normal starting position marked on the throttle quadrant

(d) Ignition was energized

(e) The fuel-supply valve was opened, allowing the engine fuel system to furnish fuel to the fuel nozzles

(f) Ignition occurred

(g) The engine accelerated slowly to 2000 rpm

(h) The starter motor was de-energized and the acceleration continued to 3000 rpm

During steps (f) through (h) the operator reduced the throttle setting only when the tail-pipe gas temperature threatened to exceed 2000° F.

Acceleration

Preceding the acceleration runs, the engine was operated at rated speed and the adjustable jet nozzle was closed until the tail-pipe gas temperature reached an equilibrium temperature of 1260° F. The engine was then throttled to the lower speed of the particular acceleration range to be covered. The engine was operated at this lower speed for sufficient time to allow all temperatures concerned to stabilize. The acceleration was accomplished by rapidly advancing the throttle control lever to the rated speed position, allowing the engine fuel regulator to automatically control engine conditions during the acceleration. During these runs the regulator high-speed stop setting was such that, in some cases, it was necessary to retard the throttle slightly from its advanced position to prevent overspeed. Possibly because of a shift in the setting of the adjustable jet nozzle during this run, the tail-pipe gas temperature stabilized at approximately 1400° F.

To obtain data at a lower temperature level during acceleration, a subsequent run was made over the same speed range with the adjustable jet nozzle opened to provide a larger area. This nozzle opening at 7950 rpm steady-state condition resulted in a tail-pipe gas temperature of approximately 1220° F.

RESULTS AND DISCUSSION

Steady-State Operation

Combustor outlet. - Figure 10 shows the results of the combustor-outlet temperature measurements at station 1 with the seven points, obtained with each probe, plotted as a temperature profile of the combustor outlet. The approximate locations of lines of constant temperature have been sketched in as dashed lines to give a better conception of the temperature zones at this station. The 1900° F center of the flame is displaced radially outward approximately 20 percent from the center of the combustor liner apparently resulting from deflection of the gases by the inclined inner surface of the transition liner just ahead of this station. It also appears that the highest temperature zone is displaced considerably to the right side of the combustor outlet. The highest temperature measured was 1940° F at the center of the transition liner $2\frac{1}{4}$ inches from the inner shell. The lowest temperature was measured by the same probe, 1/4 inch from the inner shell.

Nozzle Guide Vanes

The temperature readings obtained on 10 adjacent nozzle guide vanes covering the combustor outlet referred to previously are shown in figure 11(a). The plot of guide-vane temperatures shows that the nozzle-guide-vane temperature pattern corresponds approximately to the combustor-outlet pattern. The nozzle guide vanes behind the division points between combustors operate at temperatures on the order of 400° F cooler than vanes directly aft of the highest temperature zone of the combustor. Temperatures ranged from 1570° F on blade 7 to 1130° F on blade 2. 3403

Figure 11(b) shows a chordwise temperature profile obtained at midspan on a subsequently installed nozzle guide vane in a position corresponding to blade 6 in figure 11(a). The large temperature differentials obtained between the vane edges and the five other points on the vane are apparently due to the passage of small amounts of cooling air through the blade in the standard engine configuration used. The apparent discrepancy between the midchord temperature shown in figure 11(b), and the indicated 40-percent chord temperature shown in figure 11(a) is probably the result of the use of a different nozzle diaphragm, slight changes in the combustor fuel nozzle, and/or small changes in the internal cooling air flow in the vane.

Turbine Blades

Measured turbine-blade temperatures are shown in figure 11(c). The spanwise temperature profile shows the high-temperature region of the blade to center at approximately 60-percent span, whereas the "hot" zone of the combustor outlet appeared to correspond to about the 70-percent span position, indicating a certain amount of mixing effect as the gases flow through the passages between the nozzle guide vanes.

These data are replotted along with data obtained from another engine at various tail-pipe gas temperatures in figure 12. The turbine-blade-material temperatures change in accordance with the tail-pipe gas temperature but there is very little change in the location of the hot zone or the shape of the spanwise temperature curve.

With thermocouples installed as shown in figure 11(c) at section A-A, the chordwise temperature profile shown on the curve was obtained, which indicates a very low temperature gradient across the blade under steady-state operation.

Turbine-Wheel Temperatures

Turbine-wheel temperatures measured during cyclic operation of the engine are plotted in figure 13. The maximum temperature measured at a radius of 13.10 inches was 1185° F. The temperature at this same point fell off to 985° F during the 5-minute idle period, but the equilibrium temperature of 1185° F was reached 10 minutes after the engine reached rated speed and tail-pipe gas temperature in the following 15-minute portion of the cycle. A plot of radial temperatures measured at equilibrium conditions is shown in figure 14.

Radial temperature gradients between the thermocouples located in the center plane of the turbine wheel were calculated by dividing the measured temperature difference between two adjacent thermocouples by the distance between the points. In this manner the following steady-state gradients were obtained:

Radial location of thermocouples, in.	Temperature gradient, °F/in.
13.1 - 12.85	140
12.85 - 12.37	312
12.37 - 11.50	144
11.50 - 10.50	100
10.50 - 9.00	33

During acceleration the greatest increase in these gradients occurred in the region between the 12.85- to 12.37-inch radii locations. The gradient at this location reached a value of 343° F per inch, a 10 percent increase 3 minutes after the throttle burst. The gradient between 13.10- to 12.85-inch radii increased to 160° F per inch, a 14 percent increase over steady-state operation for this same period. The gradients between 12.37- to 11.50-inch radii and 11.50- to 10.50-inch radii showed no appreciable change during the acceleration, while the 10.50- to 9.00-inch-radii region reached a maximum of 47° F per inch, a 42 percent increase.

Transient-Temperature Measurements

Acceleration. - The temperature patterns followed by points in turbine blades and nozzle guide vanes during a rapid acceleration from 3000 to 7950 rpm are shown in figure 15. This run was made with the jet nozzle set to give a tail-pipe gas temperature of 1260° F at steady-state operation. Inadvertently the tail-pipe gas temperature actually reached 1400° F. This temperature is 125° F above the maximum allowable tail-pipe gas temperature of 1275° F. In the turbine blade (fig. 15(a)) it is seen that the leading-edge temperature follows the gas temperature changes most rapidly, while the trailing edge and midchord follow in order. The maximum temperature recorded at the leading-edge position during this run was 1630° F. Temperature differentials are set up in the blade which are of the order of 180° F from leading edge to midchord and 40° F from trailing edge to midchord.

Nozzle-guide-vane temperatures recorded during the previous run are shown in figure 15(b). The four recorded temperatures followed the gas temperature rapidly with the trailing edge, which reached a peak temperature of 1900° F, having the highest response rate. The highest temperature differential obtained was indicated between trailing edge and 3/4 chord thermocouples spaced apart by a distance of about 0.650 inch on the chord. The maximum differential shown is on the order of 750° F at the point where the trailing-edge temperature reached its peak at about 16 seconds after the start of acceleration.

A second acceleration run was made over the same speed range with the adjustable jet nozzle opened to a position which gave a tail-pipe gas temperature of approximately 1220° F at steady-state conditions. Results of this run are shown in figure 16. With the final tail-pipe gas temperature about 180° F less than the previous run, the maximum tail-pipe gas, turbine-blade, and nozzle-guide-vane temperatures during acceleration were approximately 120° F lower during this run, but temperature gradients were essentially unchanged. Rated speed was attained in 13 seconds and the tail-pipe gas temperature peak occurred 12 seconds after the start of acceleration as compared with the closed nozzle run of figure 15, where rated speed and tail-pipe gas temperature peak were attained in 16 seconds.

Normal Start

During a normal start the recorded temperatures were as shown in figure 17. The turbine-blade leading edge reached 1150° F and the nozzle-guide-vane trailing edge reached 1200° F 25 seconds after ignition. In the turbine blade (fig. 17(a)), at the time of the leading-edge first temperature peak (12 sec after ignition) a temperature differential of 590° F was recorded between the leading edge and midchord of the blade. At the same time the differential between the trailing edge and midchord was 370° F. At the same time (fig. 17(b)), a temperature difference of 530° F is shown between 3/4 chord and the trailing edge of the nozzle guide vane. The trailing edge had reached a temperature of 1025° F at this point.

Hot Start

Temperature records obtained during a hot start are shown in figure 18. At 22 seconds after ignition, the leading edge of the turbine blade had reached a peak temperature of 1860° F and the trailing edge had reached 1600° F, both points exceeding normal operating temperatures as shown in figure 11(c) for a number of seconds. Overtemperature occurred for approximately 18 seconds and 10 seconds for the leading and trailing edges, respectively. The maximum turbine-blade temperature differential during this run was 840° F between leading edge and midchord and occurred at 13 seconds after ignition. At the same time a temperature differential of 500° F was measured between the trailing edge and midchord points of the blade.

During the same hot start a temperature difference of 700° F was recorded between the nozzle-guide-vane trailing edge and 3/4 chord 14 seconds after ignition. The trailing-edge temperature reached a peak of 1850° F.

The comparative temperatures between the normal start and the hot start are tabulated as follows:

	Normal start	Hot start
Tail-pipe gas temperature peak, °F	1620	2000
Turbine-blade leading-edge peak temperature, °F	1180	1860
Turbine-blade trailing-edge peak temperature, °F	920	1600
Nozzle-guide-vane trailing edge, °F	1200	1860

Temperature differential plots were made of recorded turbine-blade temperatures showing the magnitude of leading edge to midchord, and trailing edge to midchord temperature differences for each of the transient runs described. Figure 19 shows the resulting curves for the acceleration, the normal start, and the hot start, respectively. The leading edge and, to a somewhat lesser degree, the trailing edge of a J47 turbine blade will be subjected to rapid temperature changes of considerable magnitude in the course of normal engine operation. The slower temperature response of the midchord region of the blade to the rapidly changing gas temperature during transient conditions will inevitably cause thermal stresses of considerable magnitude in the blade structure. Since the midchord region of the blade is of greater thickness it follows that temperature cycling of a turbine blade may have a deteriorating effect on the leading and trailing edges of the blade.

Analytical methods for determining the rate of response of material temperature of the leading edge and midchord of the turbine blade to changes in gas temperature are presented in reference 2. While such an analysis is not within the intended scope of this report, the use of these methods would permit the prediction of temperature gradients when the engine is operated through any given sequence of operation.

Figure 20 shows temperature differences measured between thermocouples at 3/4 chord and trailing edge on the nozzle guide vane during the transient runs described previously. The normal starting run (fig. 20 (a)) shows the lowest maximum differential of 540° F, the hot start gave a peak differential of 700° F, and the highest differentials were recorded during the rapid accelerations (fig. 20(b)). During the run with the nozzle setting that resulted in 1400° F tail-pipe gas at steady-state operation, the peak temperature difference was 770° F 16 seconds after start of acceleration. With the larger jet-nozzle area, the peak differential was 780° F and occurred 12 seconds after beginning acceleration. 3403

Table I has been prepared to show conveniently the relation between the operating conditions and the turbine-blade and nozzle-guide-vane temperatures. The number of the figure from which the data were obtained has also been included.

SUMMARY OF RESULTS

Within the range of engine conditions explored in this investigation to determine engine operating conditions causing the severe thermal stresses in the hot parts of a turbojet engine:

1. The turbine wheel achieved its maximum center plane rim temperature of 1185° F at a radius of 13.1 inches within 10 minutes after acceleration from idle- to full-power conditions.

2. Measurements of the temperature of nozzle guide vanes across a combustor outlet indicated that under steady-state full-power conditions the temperature difference between the hottest and coldest nozzle vane (depending on location in relation to combustor outlet) was on the order of 400° F.

3. Under steady-state full-power conditions with 1260° F tail-pipe gas temperature, the turbine blade reached a maximum of about 1470° F at the leading edge and the nozzle vanes reached a maximum of about 1700° F at the trailing edge.

4. Normal transient conditions of starting and acceleration from idle to rated speed were investigated for their effect on peak temperatures and temperature differences. During normal starting the turbine-blade peak temperatures were less than the steady-state maximum, but during acceleration the leading-edge temperatures increased from 40° to 170° F over the final steady-state temperatures. The most severe temperature differential occurred during starting and was of the order of 600° F between leading edge and midchord.

5. During the normal starting the nozzle-vane temperatures were less than steady-state maximums, but during acceleration from idle to rated speed the trailing-edge temperature increased from 110° to 190° F over final steady-state temperatures. The most severe temperature differentials were noted between 3/4 chord and trailing edge during acceleration and were approximately 775° F.

6. The conditions of an accidental hot start were duplicated by allowing tail-pipe gas temperatures to go 400° F over the normal 1600° F maximum for about 17 seconds. This condition caused peak temperatures of the blade leading edge and nozzle-vane trailing edge to rise as high as 1860° F. The maximum differences in the turbine blade were 850° F, 250° F higher than during a normal start. The gradients in the nozzle vane during the hot start were greater than those measured during a normal start but were no more severe than the temperature gradients that occur during engine acceleration.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 9, 1954

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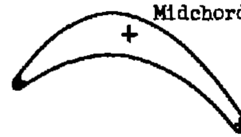
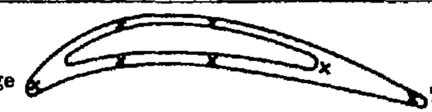
2. Hodd, Richard, and Phillips, William E., Jr.: Dynamic Response of Turbine-Blade Temperature to Exhaust-Gas Temperature for Gas-Turbine Engines. NACA RM E52A14, 1952.

TABLE I. - RELATION OF OPERATING CONDITIONS TO TURBINE-BLADE AND NOZZLE-VANE MATERIAL TEMPERATURES

	Peak temperature			Maximum chordwise gradient		
	Temperature, °F	Location	Reference figure	Temperature, °F	Location (a)	Figure
						
Turbine Blade						
Steady state (Tail-pipe gas 1260° F, 7950 rpm)	1470	Leading edge	11(c)	30	LE to TE	11(c)
Normal start (Tail-pipe gas 1620° F peak)	1180	Leading edge	17(a)	600	LE to MC	19(b)
Hot start (Tail-pipe gas 2000° F peak)	1860	Leading edge	18(a)	850	LE to MC	19(c)
Acceleration (idle to rated speed)						
a. Tail-pipe gas 1620° F peak; 1400° F final	1630	Leading edge	15(a)	185	LE to MC	19(a)
b. Tail-pipe gas 1490° F peak; 1220° F final	1510	Leading edge	16(a)	170	LE to MC	19(a)
						
Nozzle Vane						
Steady state (Tail-pipe gas 1260° F, 7950 rpm)	1700	Trailing edge	11(b)	300	3/4 Chord to TE	11(b)
Normal start (Tail-pipe gas 1620° F peak)	1220	Trailing edge	17(b)	540	3/4 Chord to TE	20(a)
Hot start (Tail-pipe gas 2000° F peak)	1860	Trailing edge	18(b)	710	3/4 Chord to TE	20(a)
Acceleration (idle to rated speed)						
a. Tail-pipe gas 1620° F peak; 1400° F final	1920	Trailing edge	15(b)	770	3/4 Chord to TE	20(b)
b. Tail-pipe gas 1490° F peak; 1220° F final	1790	Trailing edge	16(b)	780	3/4 Chord to TE	20(b)

[a] Leading edge, LE; trailing edge, TE; midchord, MC.

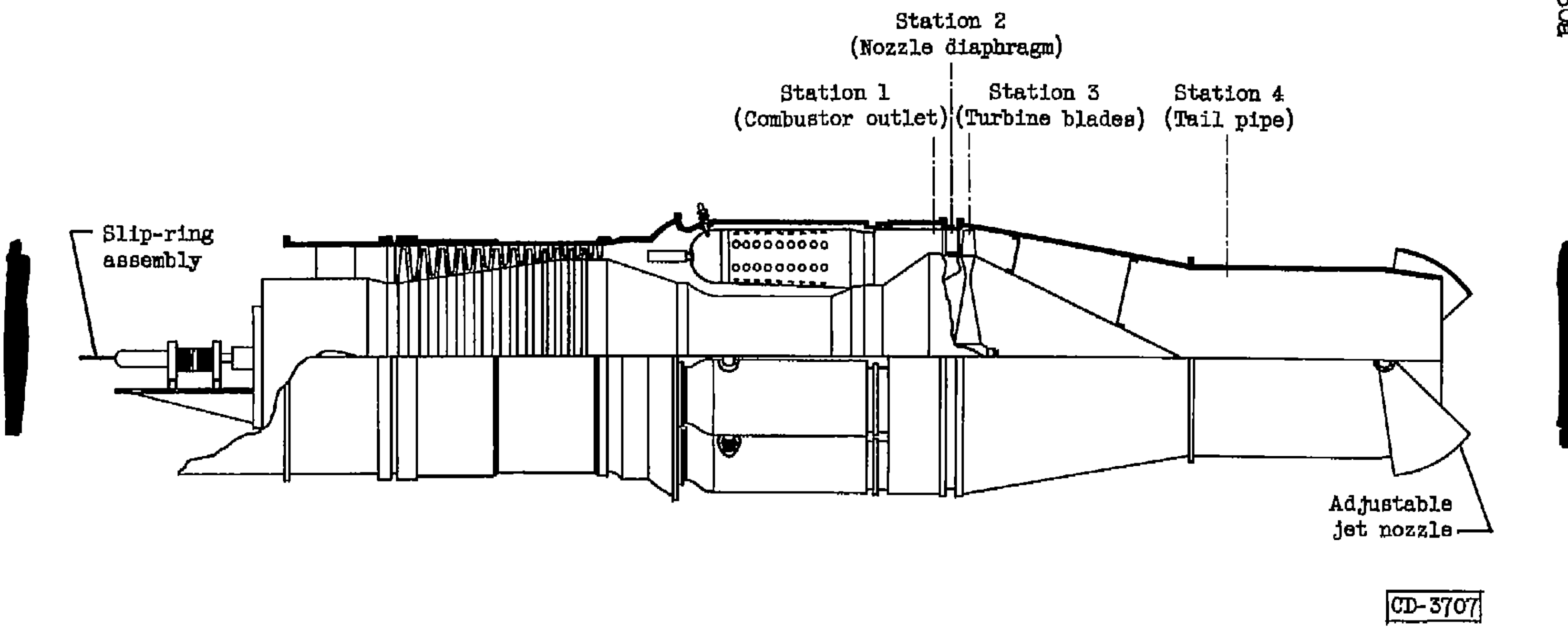
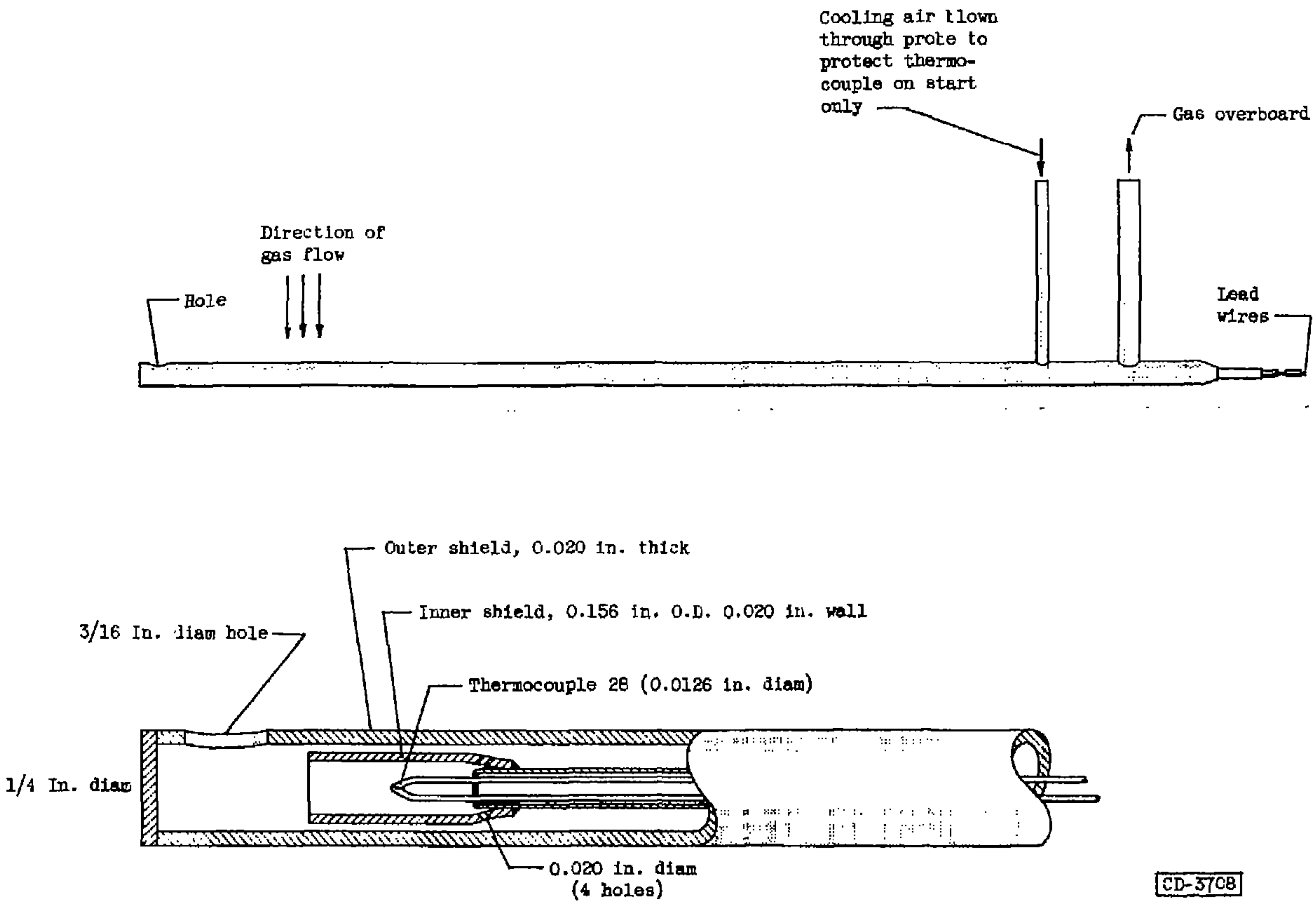
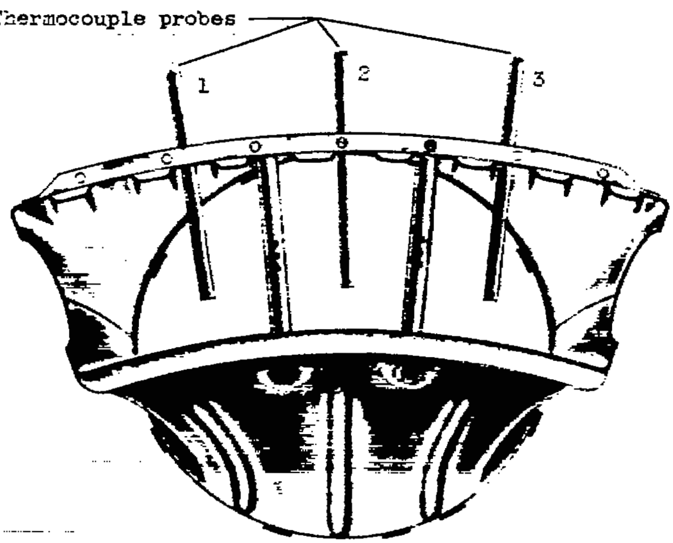


Figure 1. - J47-25 engine instrumentation.

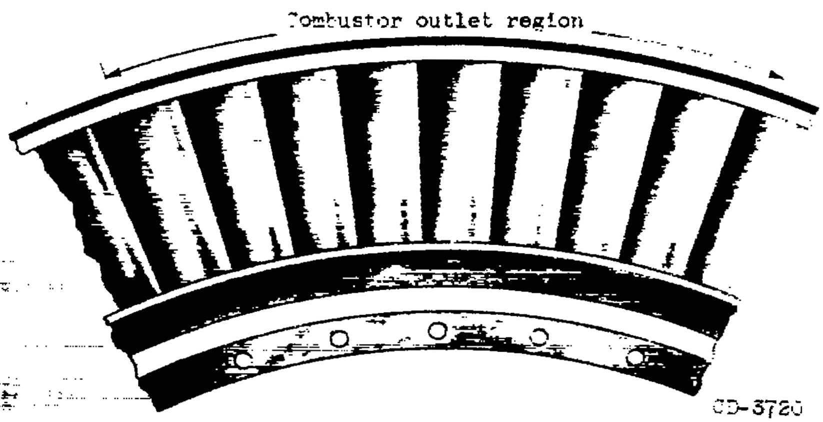


Englarged section of tip

Figure 2. - Double-shielded aspirated thermocouple probe.



(a) Transition liner; axial view looking forward.



(b) Nozzle diaphragm region covered by No. 1 combustor.

Figure 3. - Combustor outlet and adjoining nozzle-guide-vane configuration.

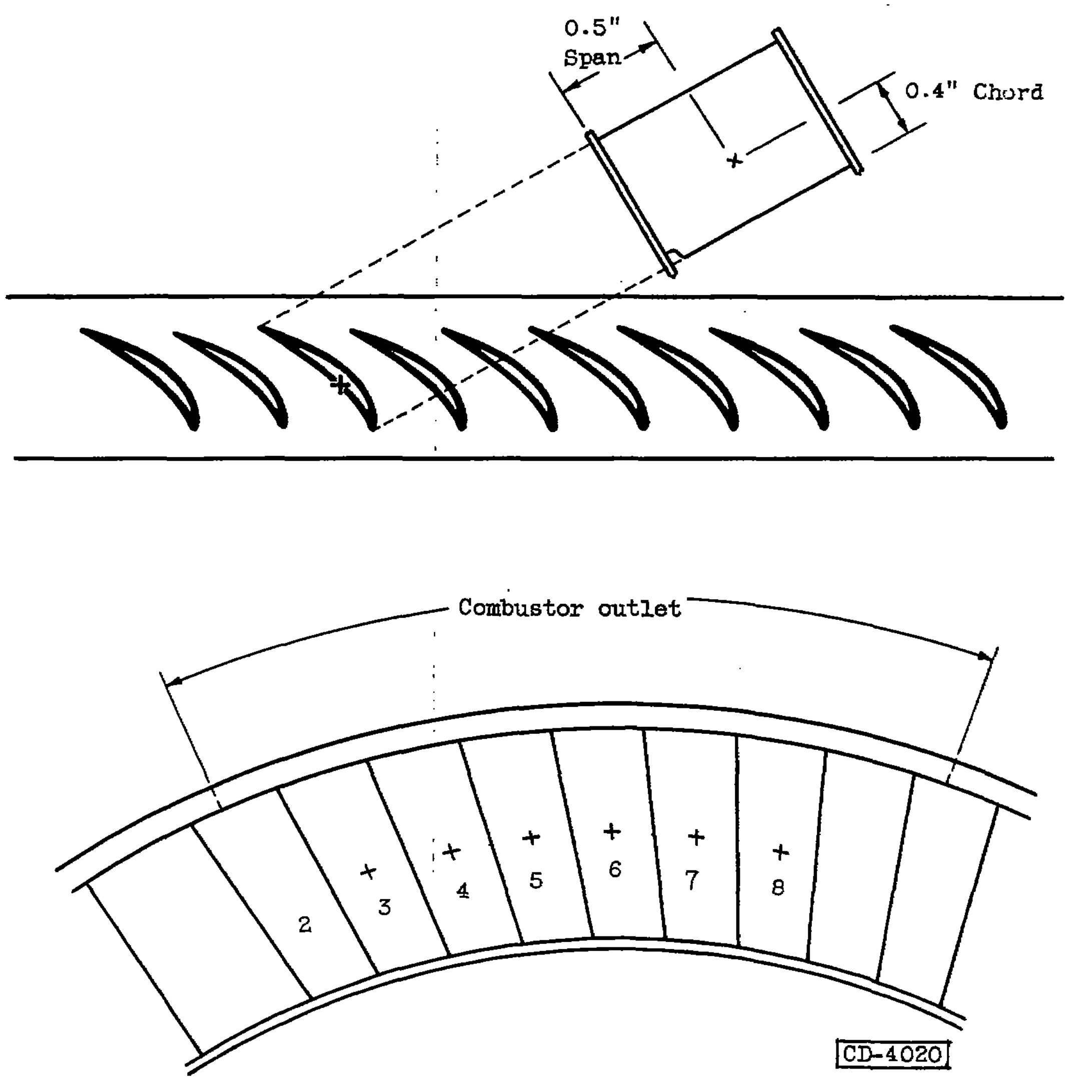


Figure 4. - Thermocouple location for nozzle diaphragm and combustor-outlet survey.

3403

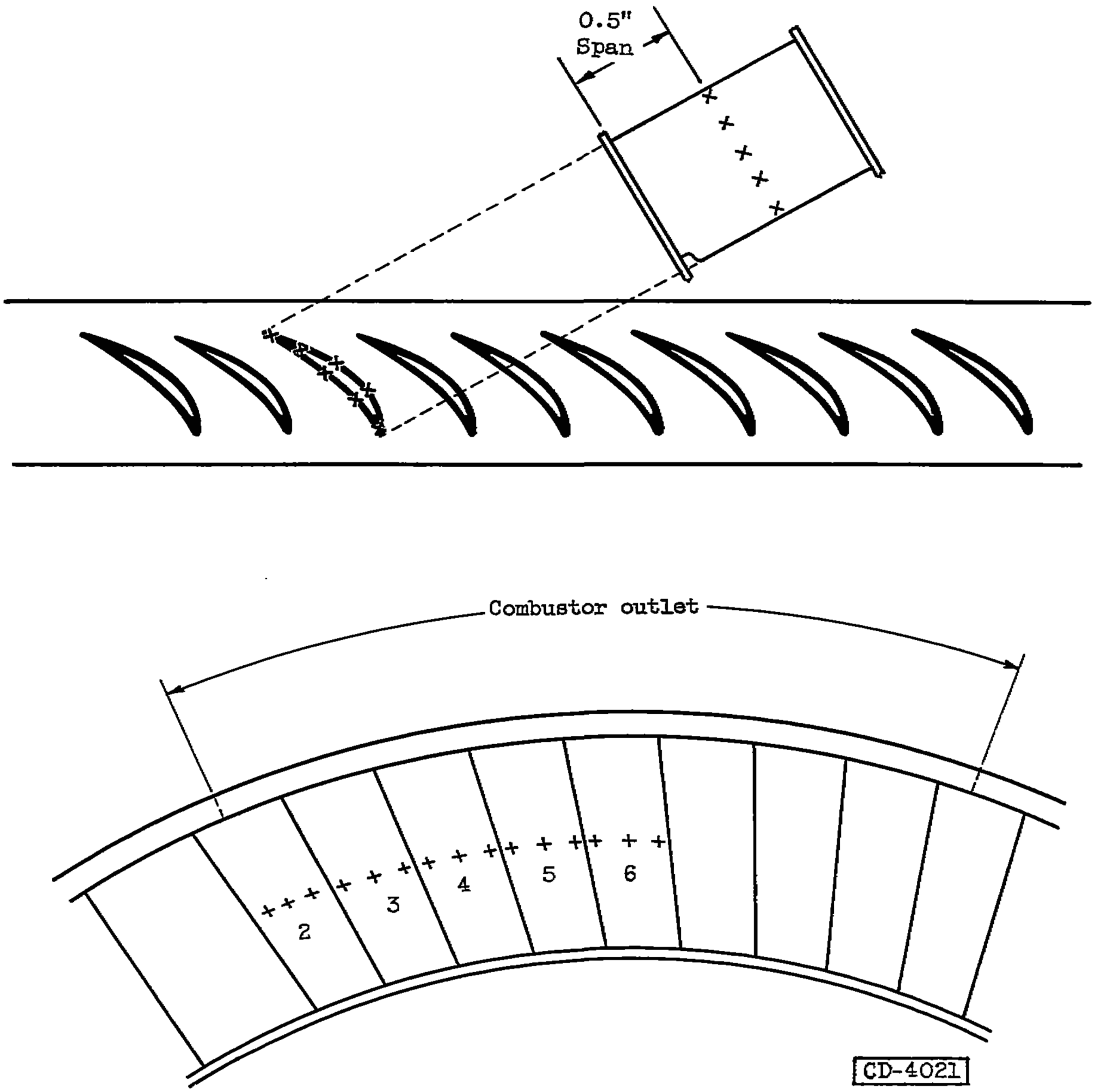


Figure 5. - Thermocouple location for chordwise temperature survey of nozzle guide vanes.

3403

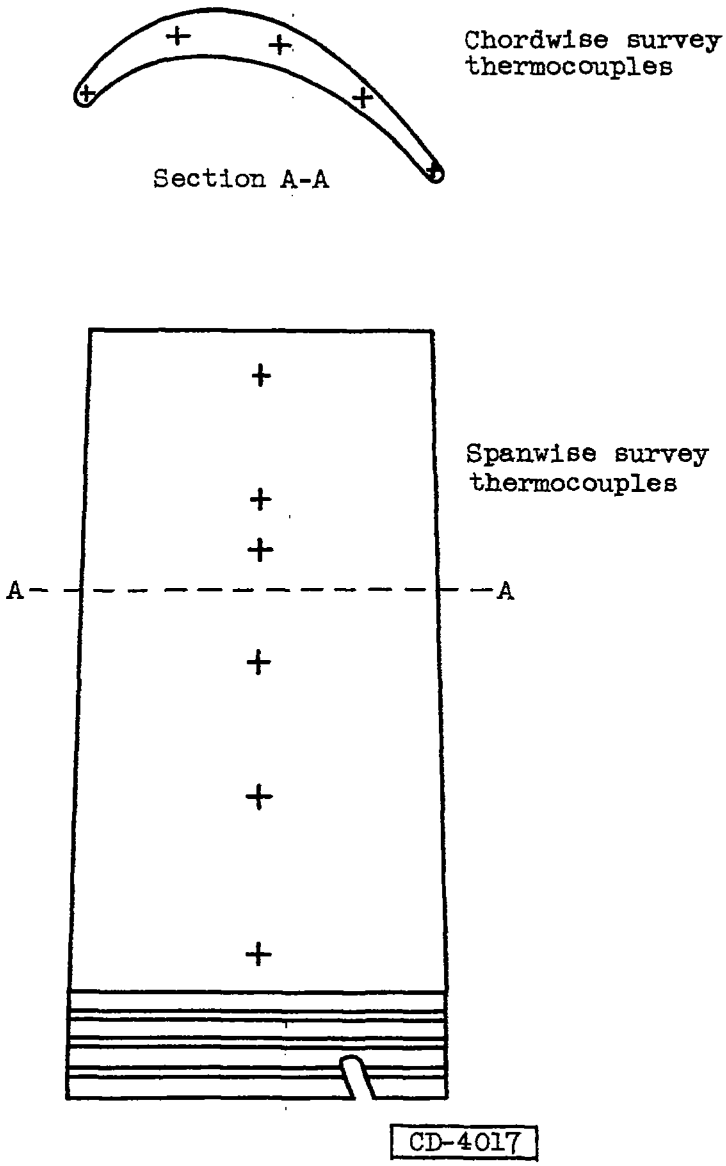
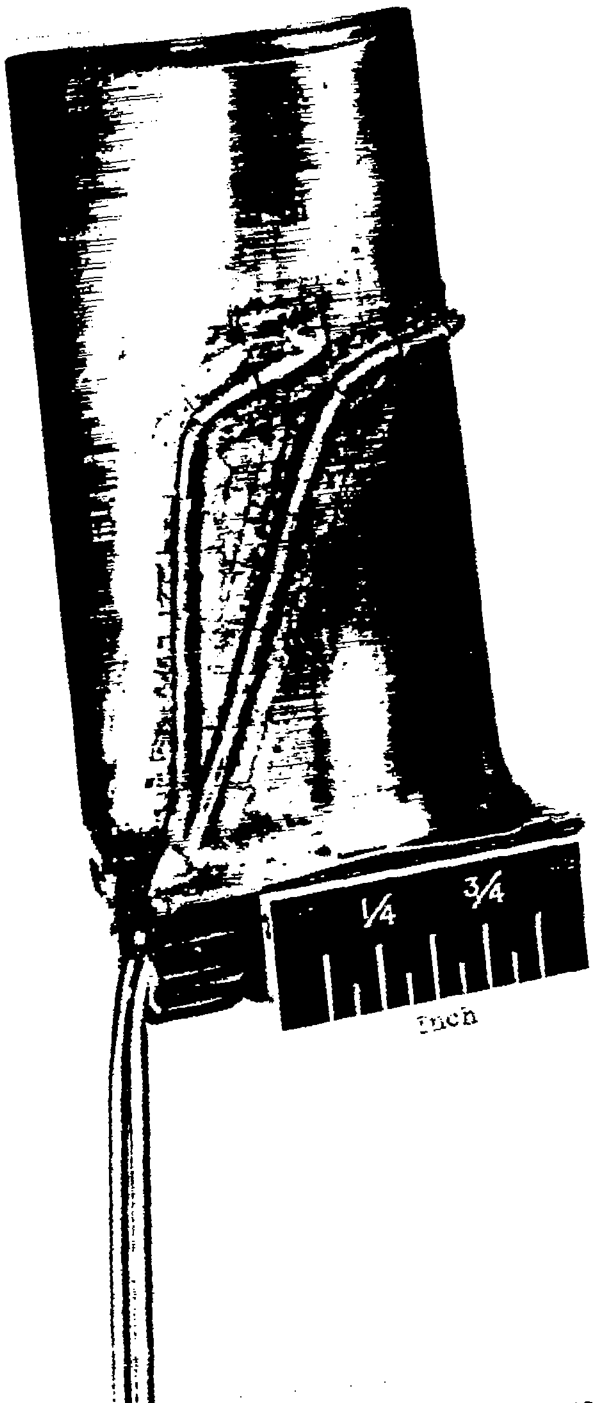


Figure 6. - Location of thermocouples on turbine blades.

[redacted]

3403



C-36354

Figure 7. - Turbine blade showing typical thermocouple installation.

[redacted]

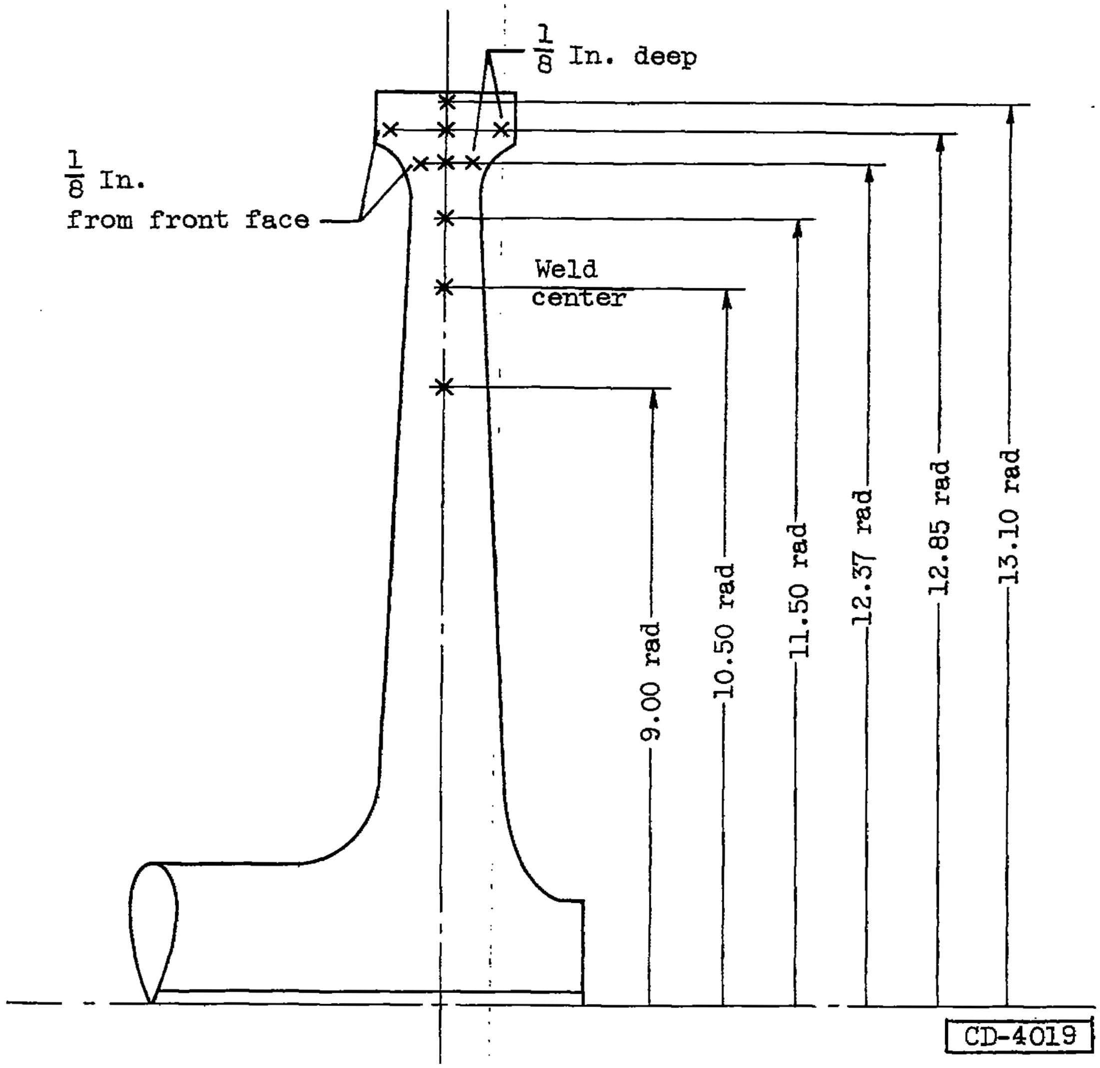


Figure 8. - Turbine-wheel section showing thermocouple location.

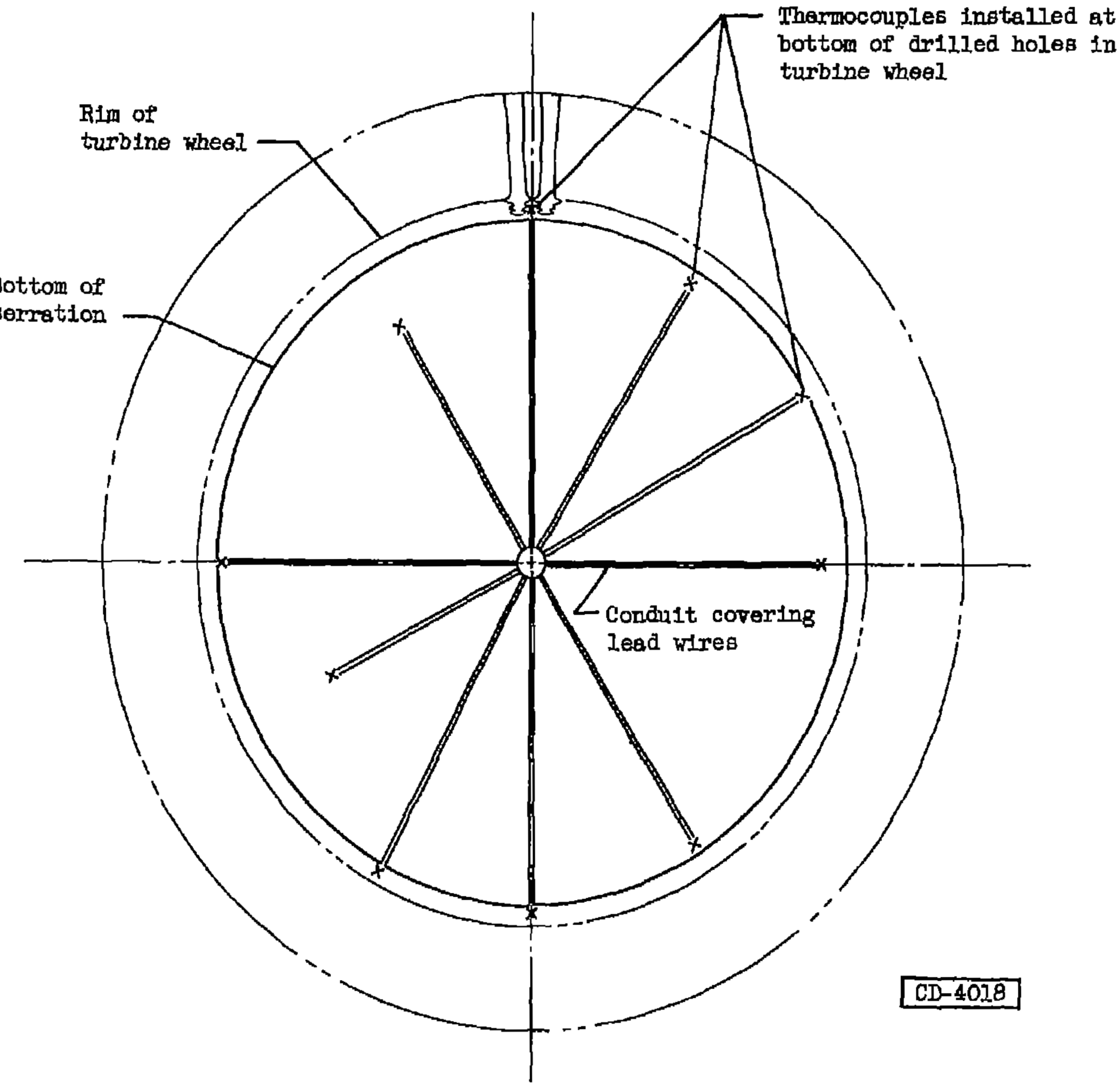


Figure 9. - Instrumentation of rear face of turbine wheel.

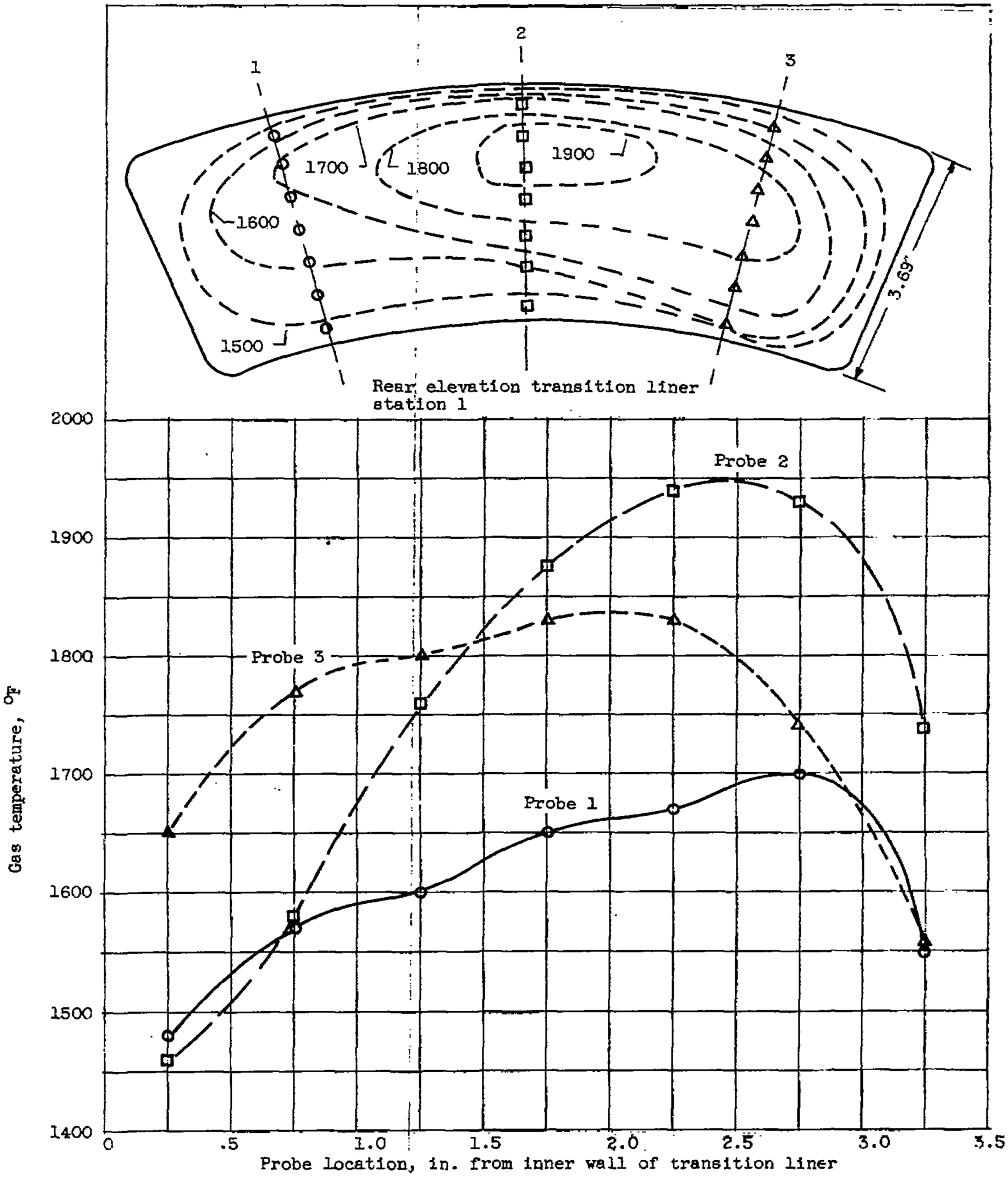
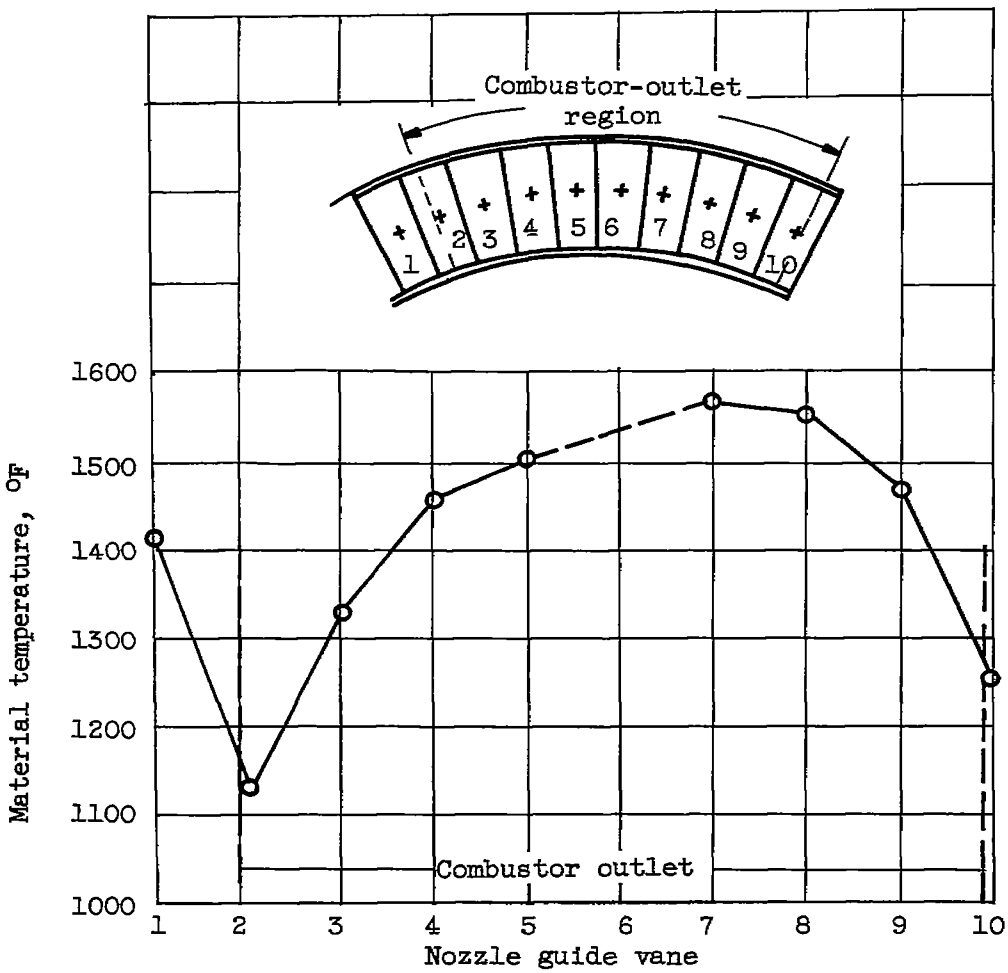


Figure 10. - Temperature distribution in J47-25 combustor transition liner.

3403

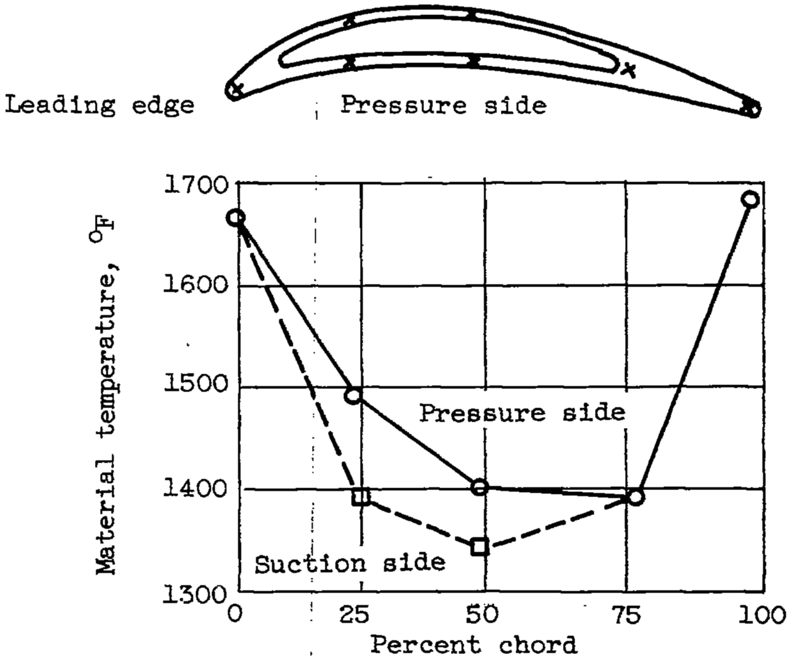
CD-4 back



(a) Nozzle guide vane. Combustor-outlet survey.

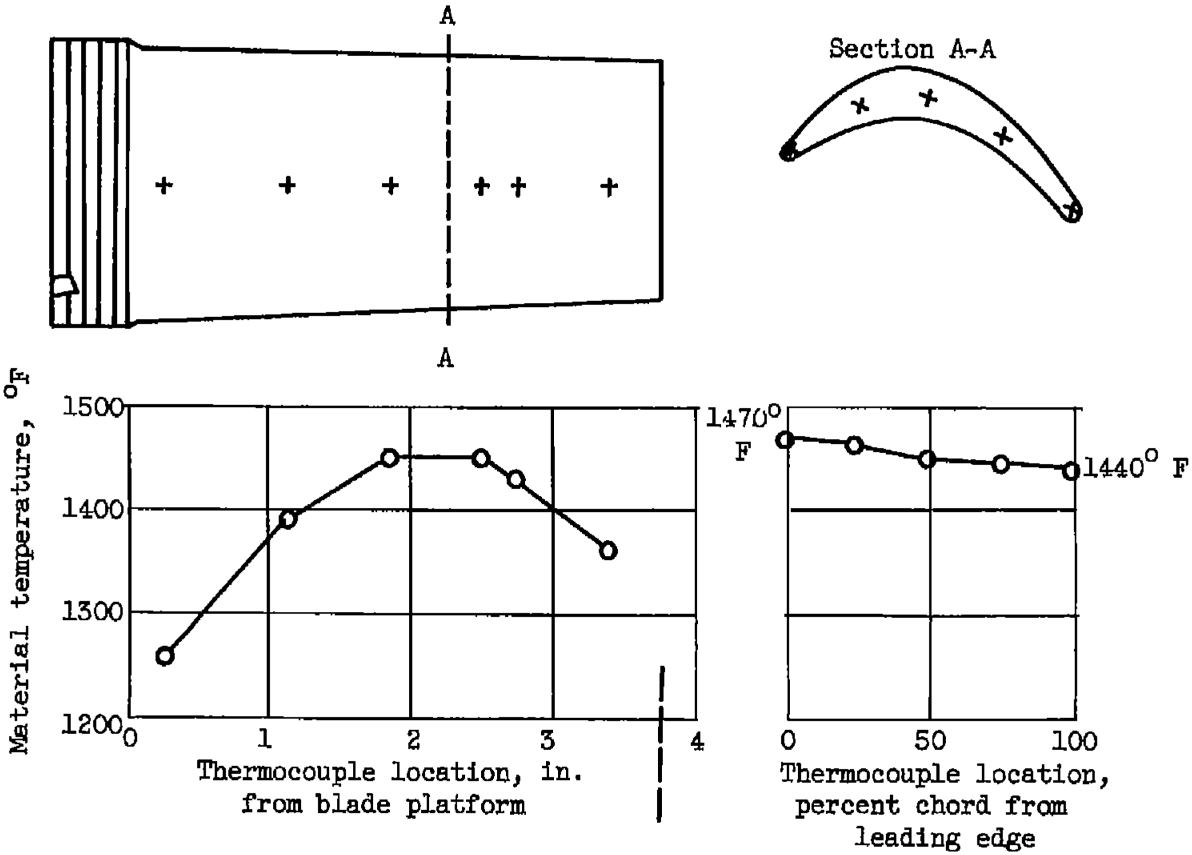
Figure 11. - Steady-state temperatures. Engine speed, 7950 rpm; tail-pipe gas temperature, 1260° F; sea-level test stand.

3403



(b) Nozzle guide vane. Chordwise survey at midspan.

Figure 11. - Continued. Steady-state temperatures. Engine speed, 7950 rpm; tail-pipe gas temperature, 1260° F; sea-level test stand.

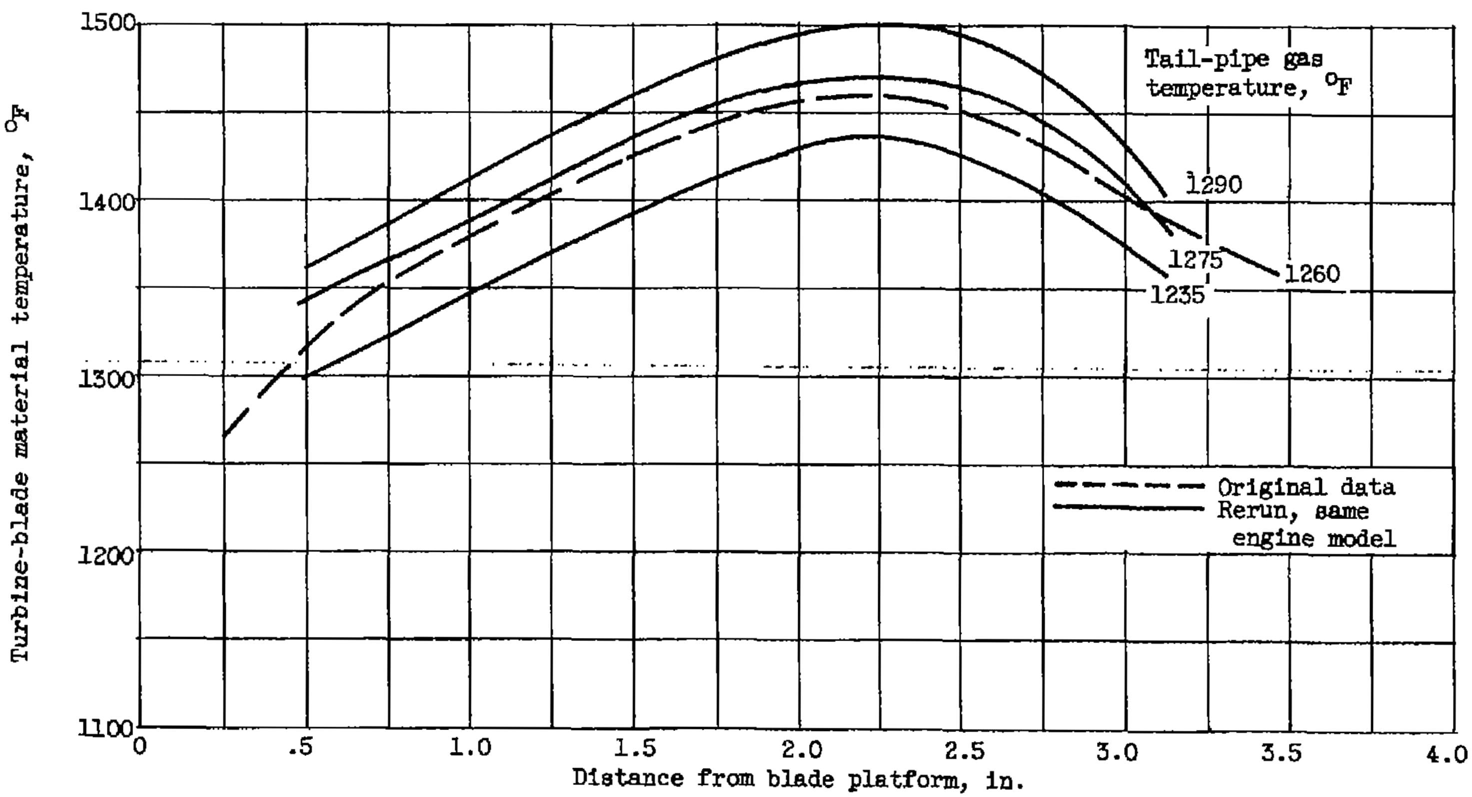


(c) Turbine blade.

Figure 11. - Concluded. Steady-state temperatures. Engine speed, 7950 rpm; tail-pipe gas temperature, 1260° F; sea-level test stand.

[redacted]

[redacted]



[redacted]

Figure 12. - Relation of tail-pipe gas temperature to blade material temperature at constant engine speed (7950 rpm). J47-25 engine spanwise temperature survey at midchord.

[redacted]

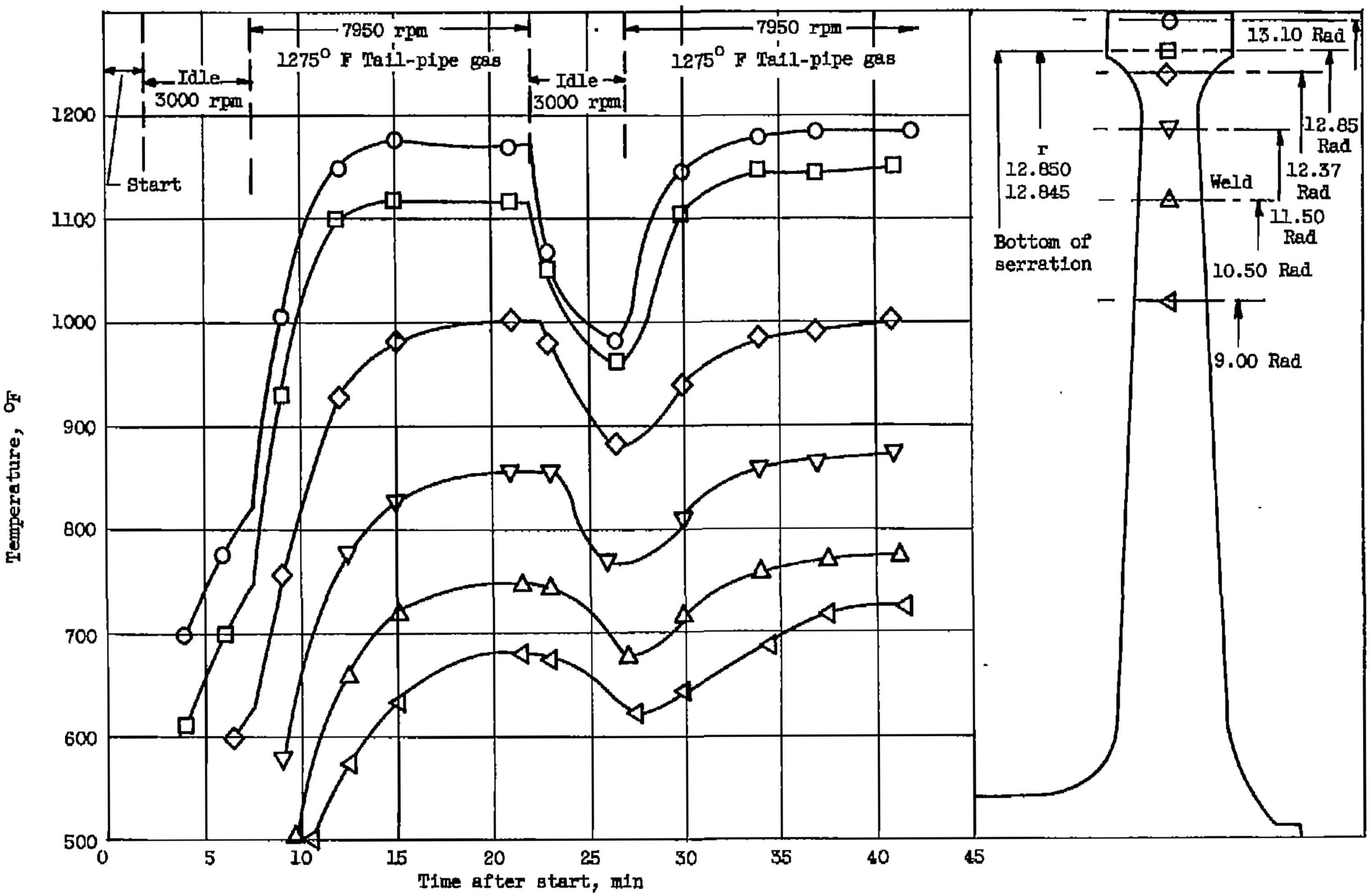


Figure 13. - Turbine-wheel temperatures during cyclic operation: 5 minutes at 3000 rpm; 15 minutes at 7950 rpm.

[redacted]

3403

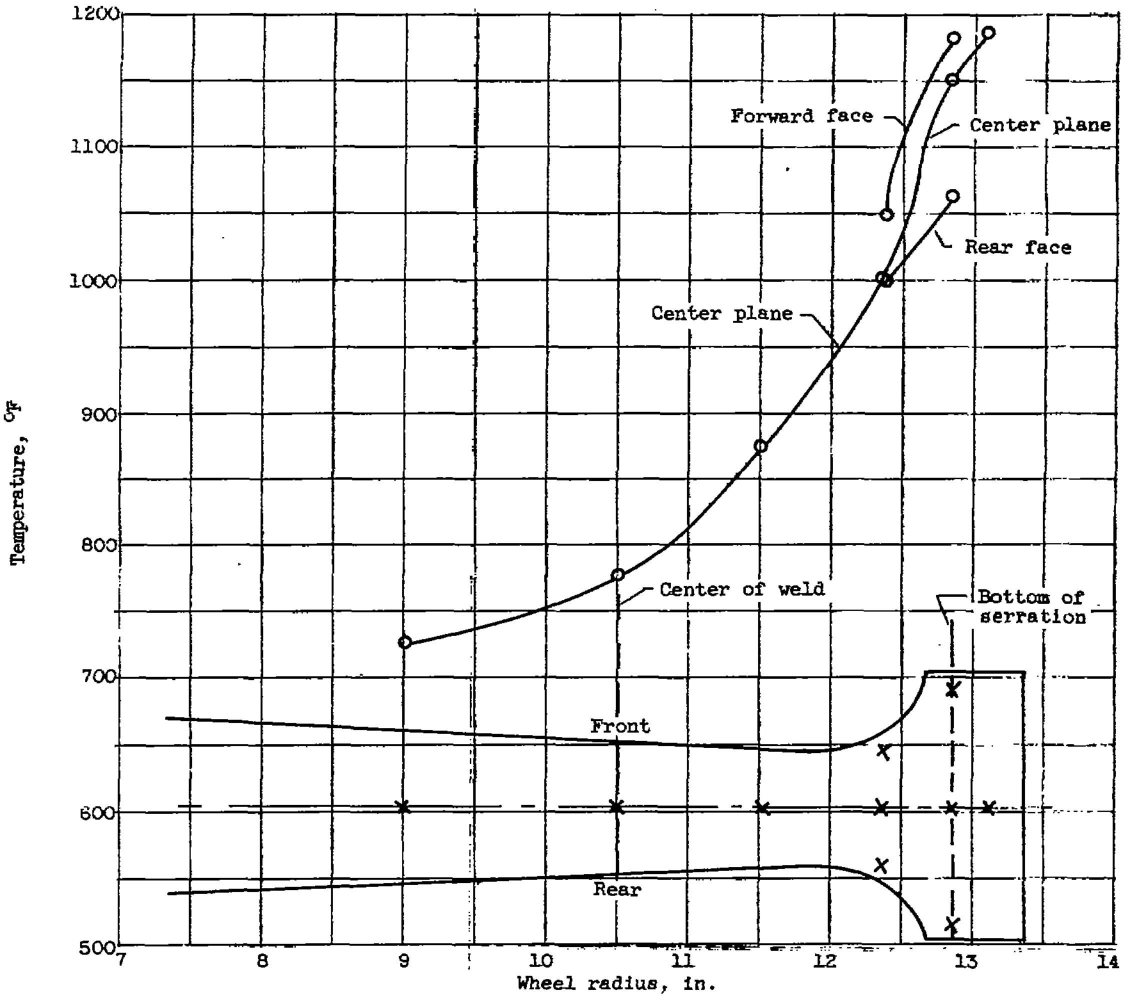
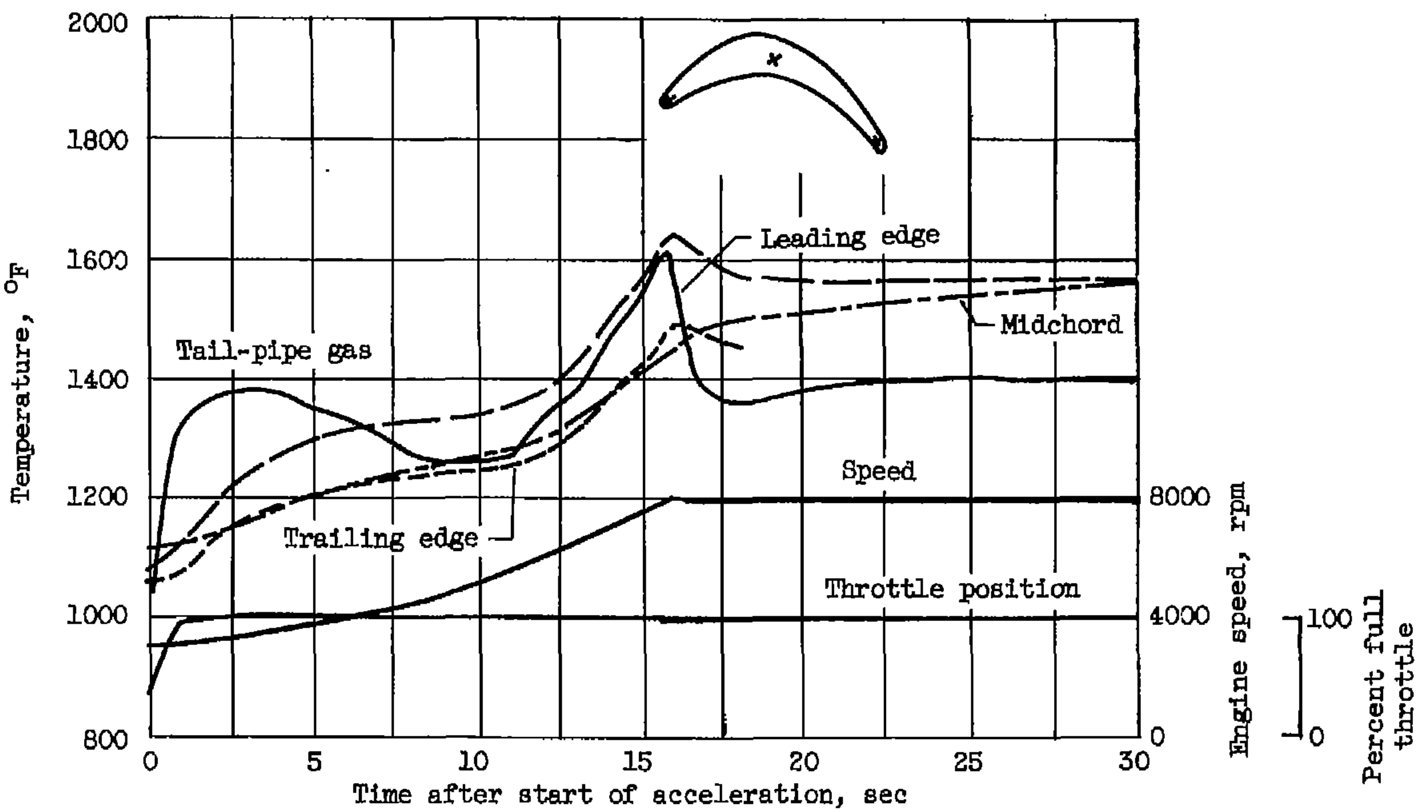


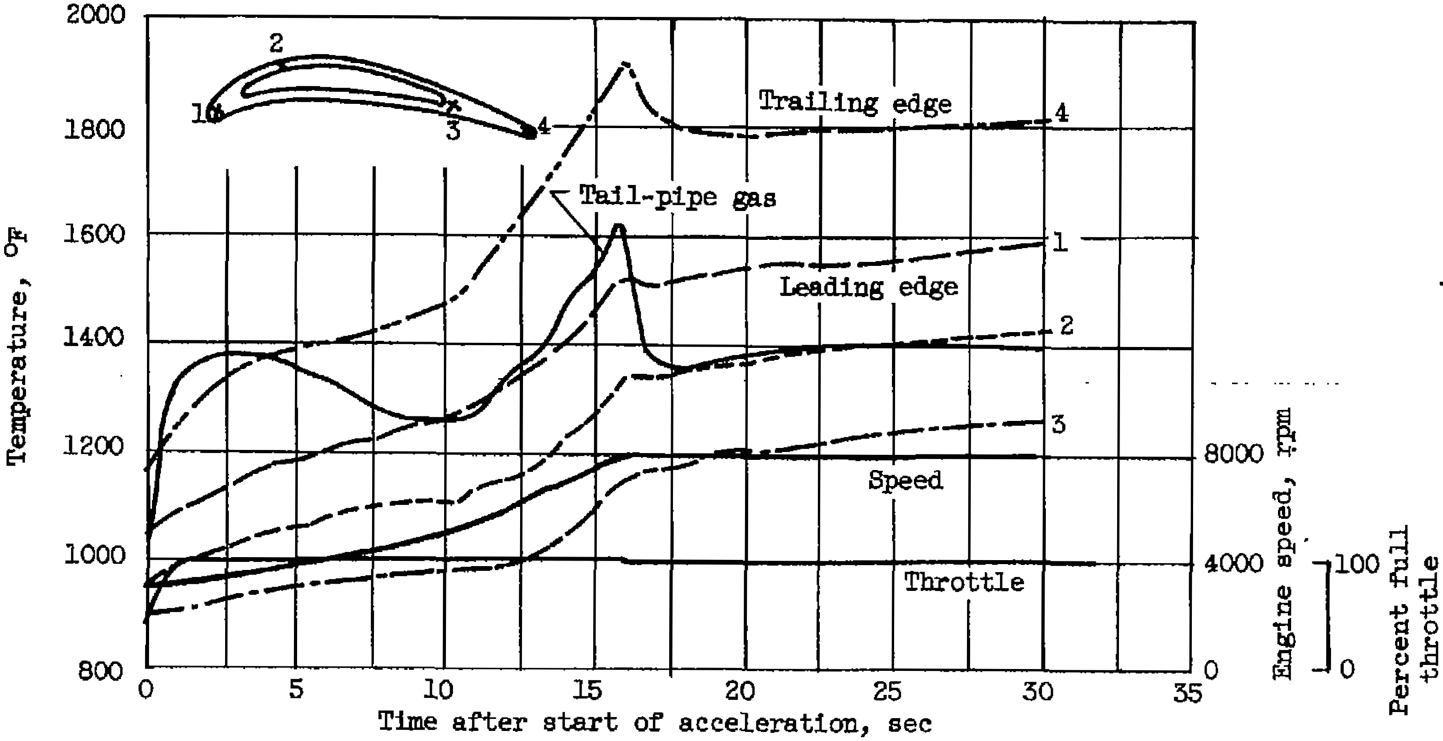
Figure 14. - Equilibrium temperatures in turbine disk. Engine speed, 7950 rpm; tail-pipe gas temperature 1275° F.



(a) Turbine blade.

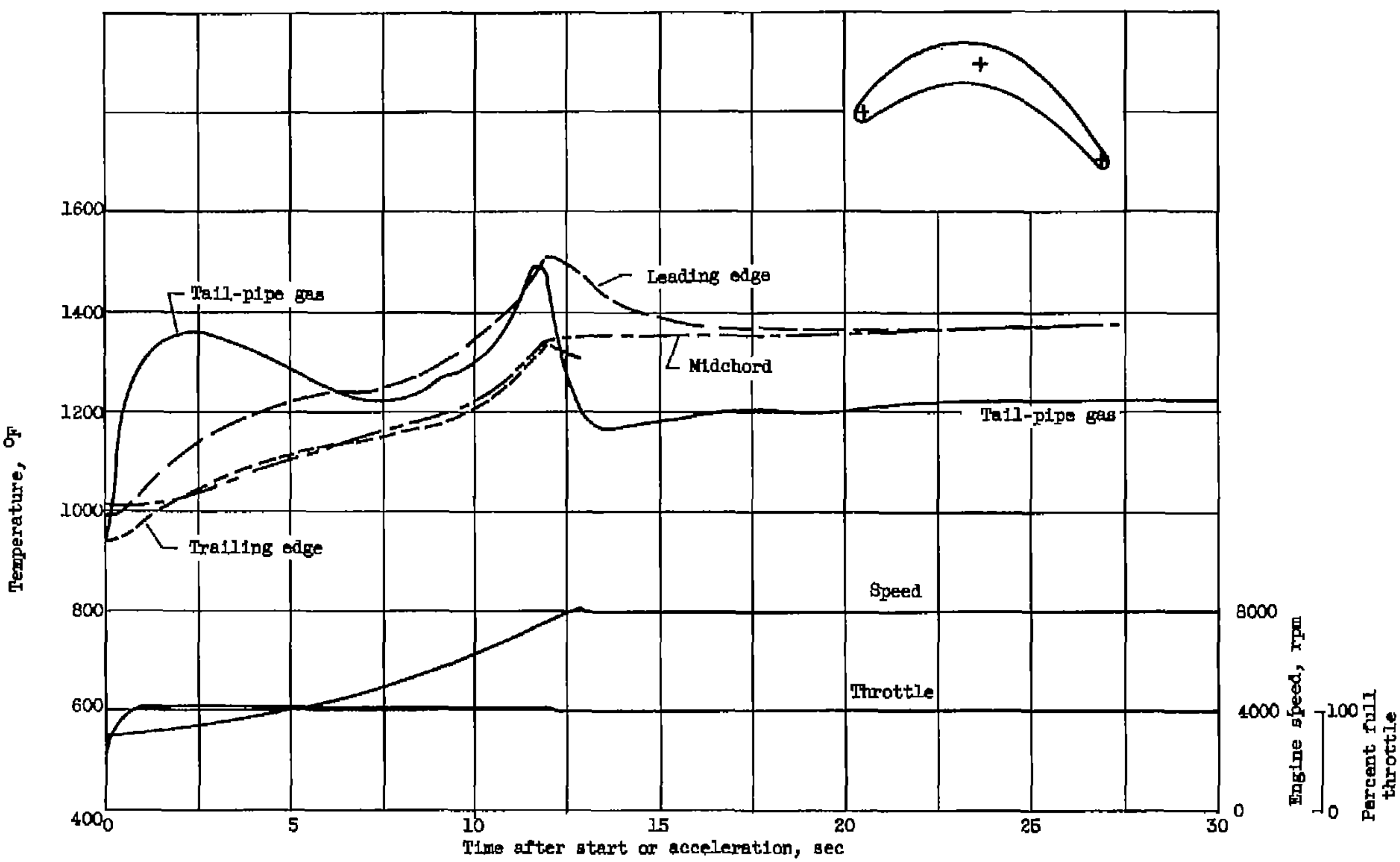
Figure 15. - Transient temperatures during acceleration from idle (3000 rpm) to rated speed (7950 rpm). Closed jet nozzle.

[redacted]



(b) Nozzle guide vane.

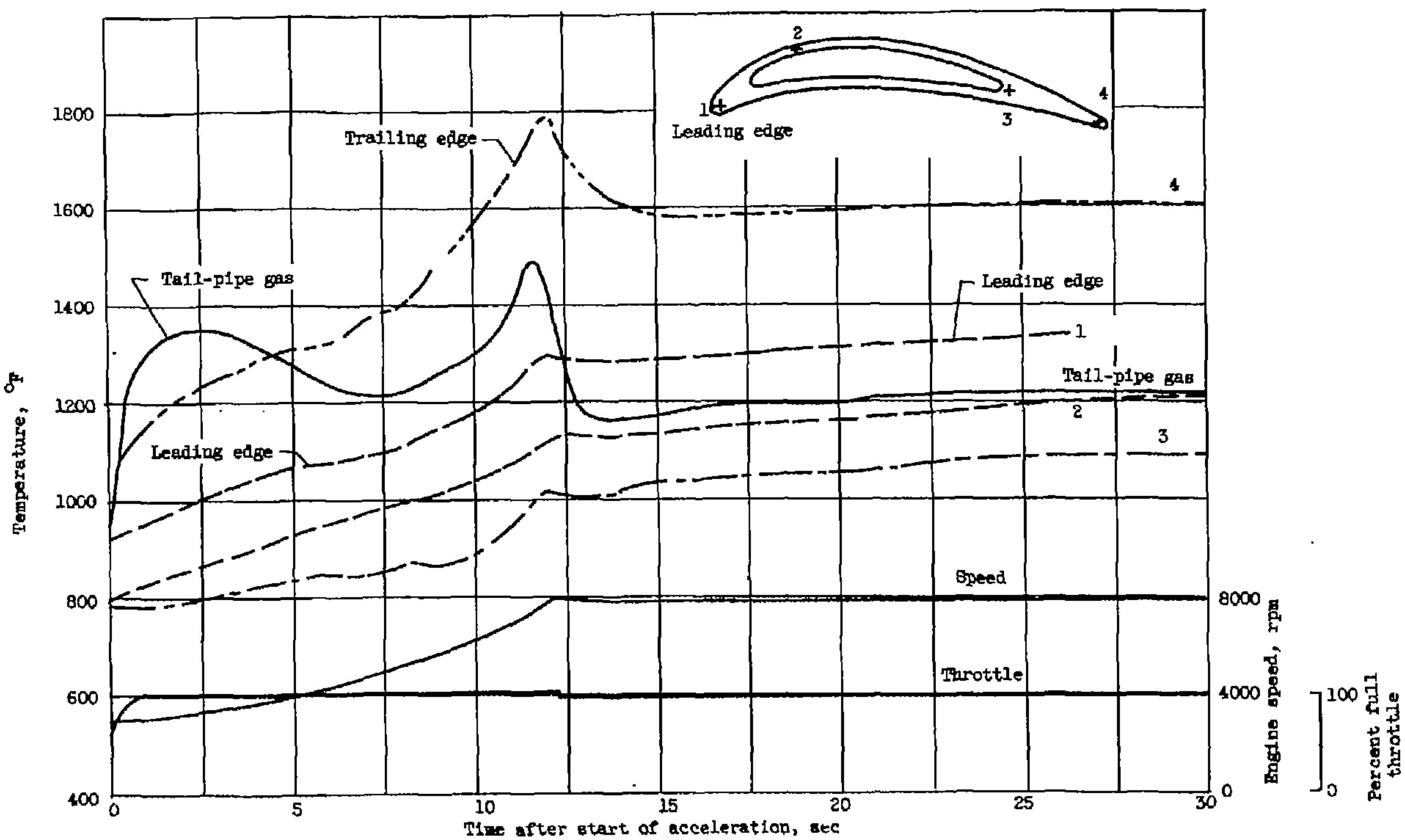
Figure 15. - Concluded. Transient temperatures during acceleration from idle (3000 rpm) to rated speed (7950 rpm). Closed jet nozzle.



(a) Turbine blade.

Figure 16. - Transient temperatures during acceleration from idle (3000 rpm) to rated speed (7950 rpm). Open jet nozzle.

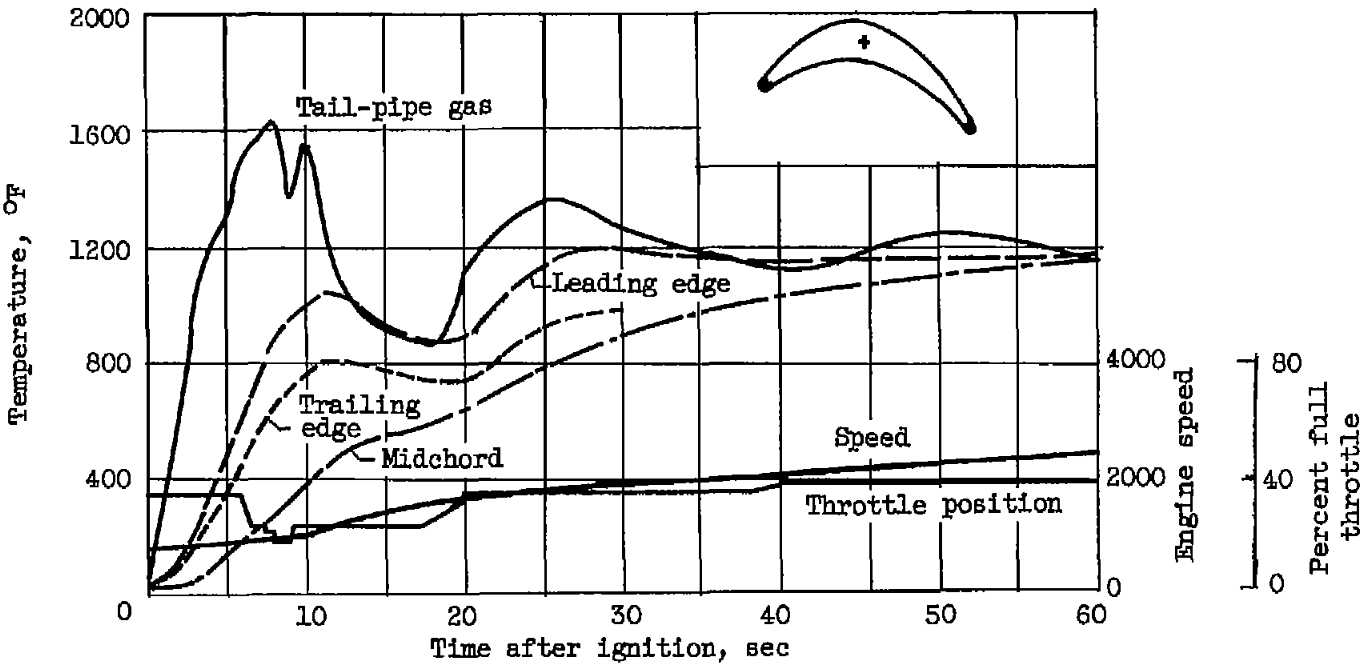
[redacted]



(b) Nozzle guide vane.

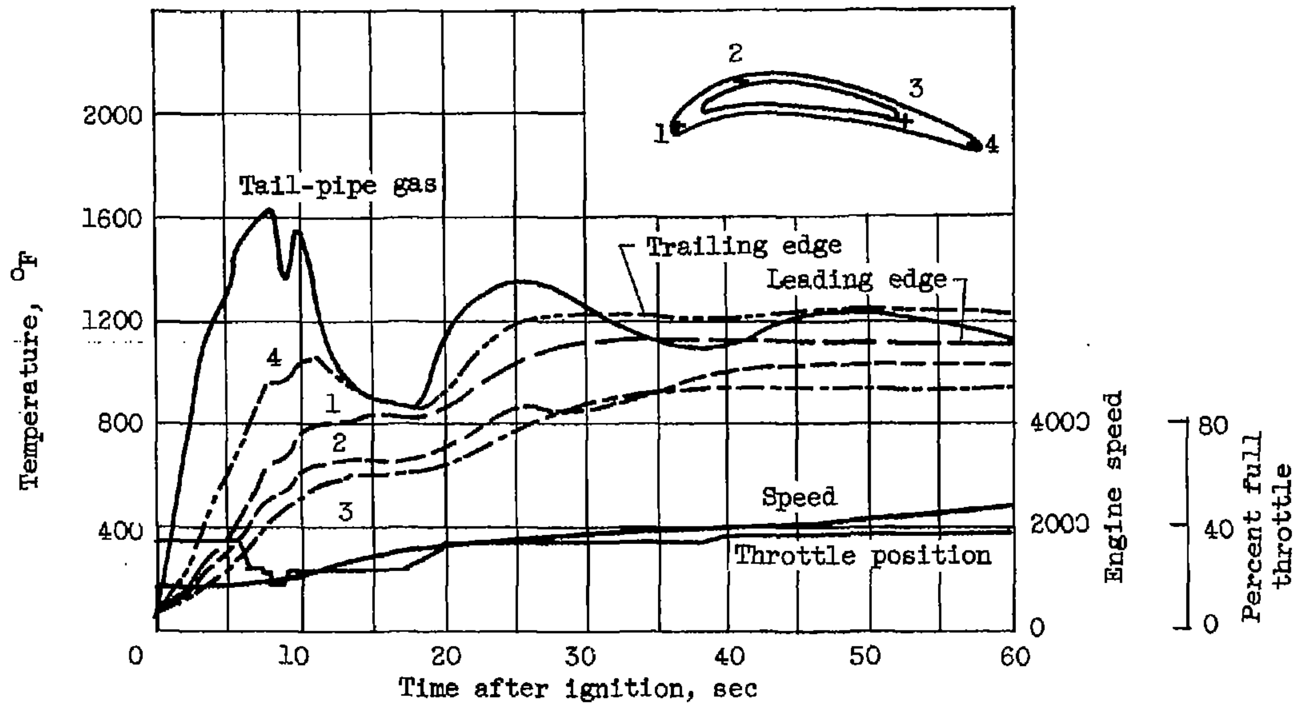
Figure 16. - Concluded. Transient temperatures during acceleration from idle (3000 rpm) to rated speed (7950 rpm). Open jet nozzle.

[redacted]



(a) Turbine blade.

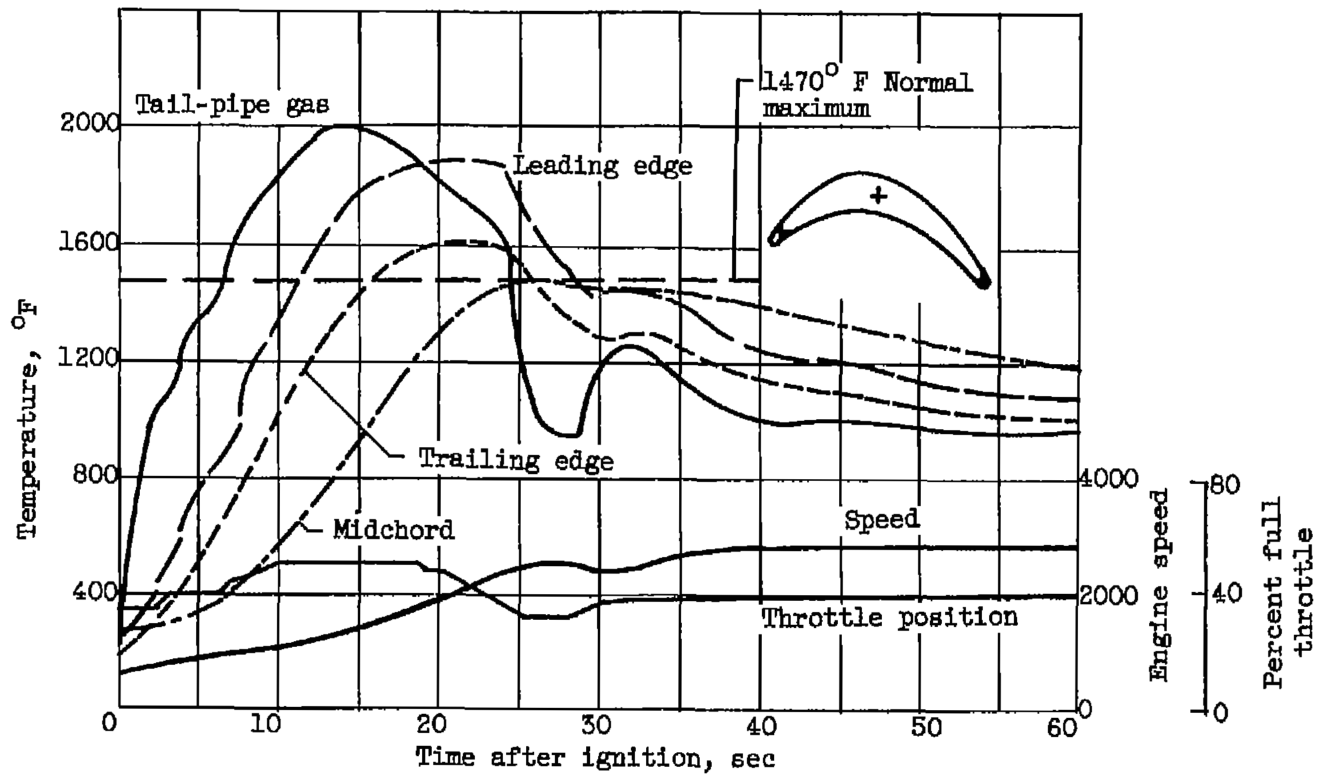
Figure 17. - Transient temperatures during normal start.



(b) Nozzle guide vane.

Figure 17. - Concluded. Transient temperatures during normal start.

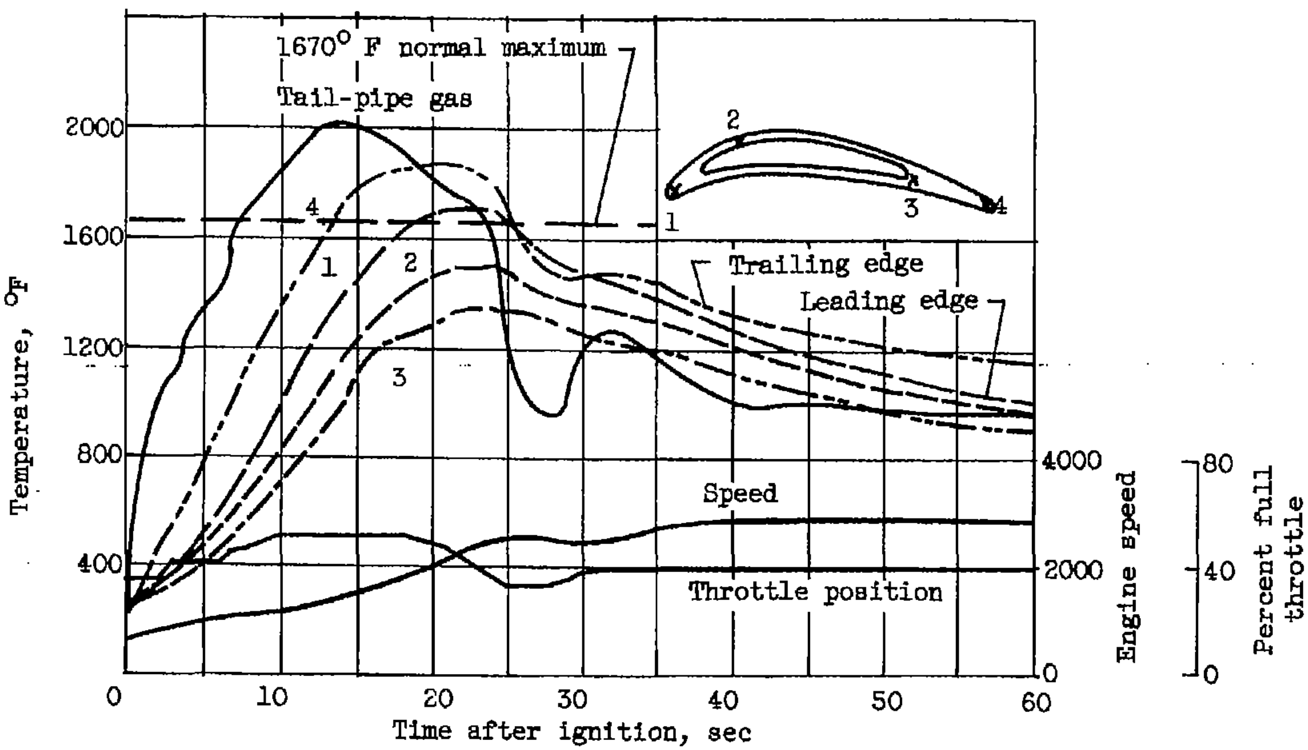
[redacted]



(a) Turbine blade.

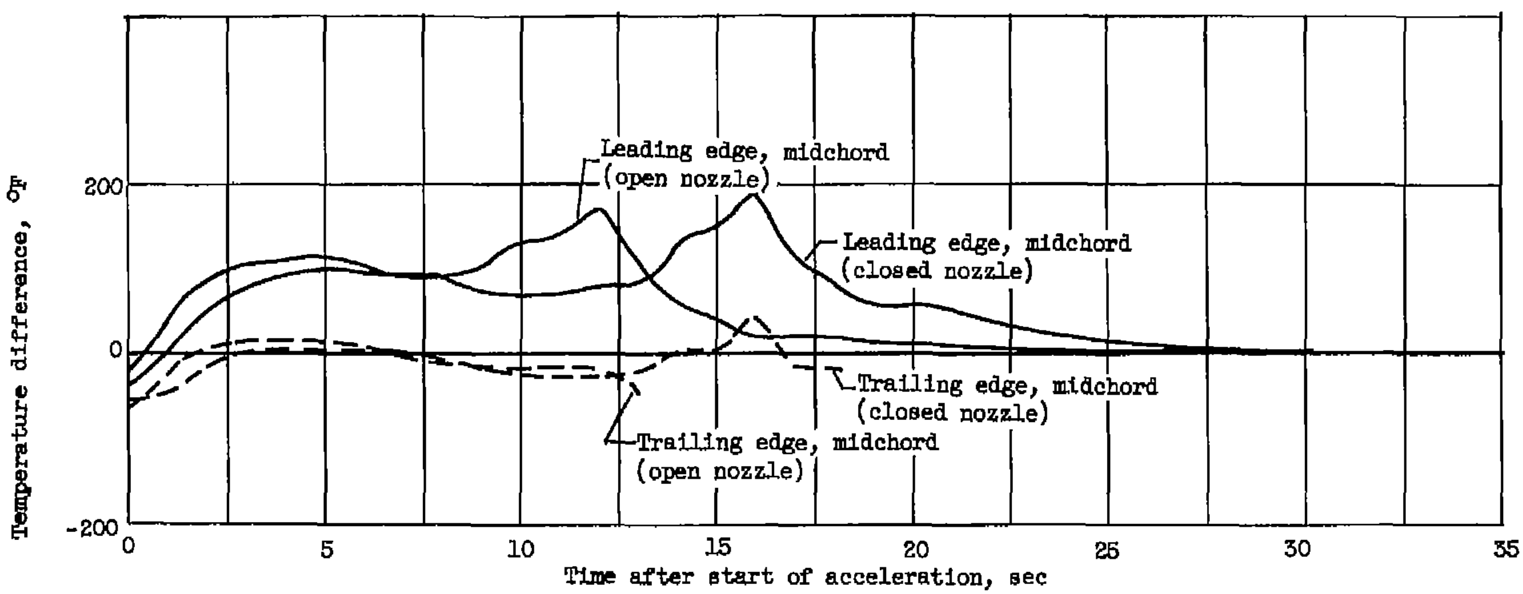
Figure 18. - Transient temperatures during hot start.

[redacted]



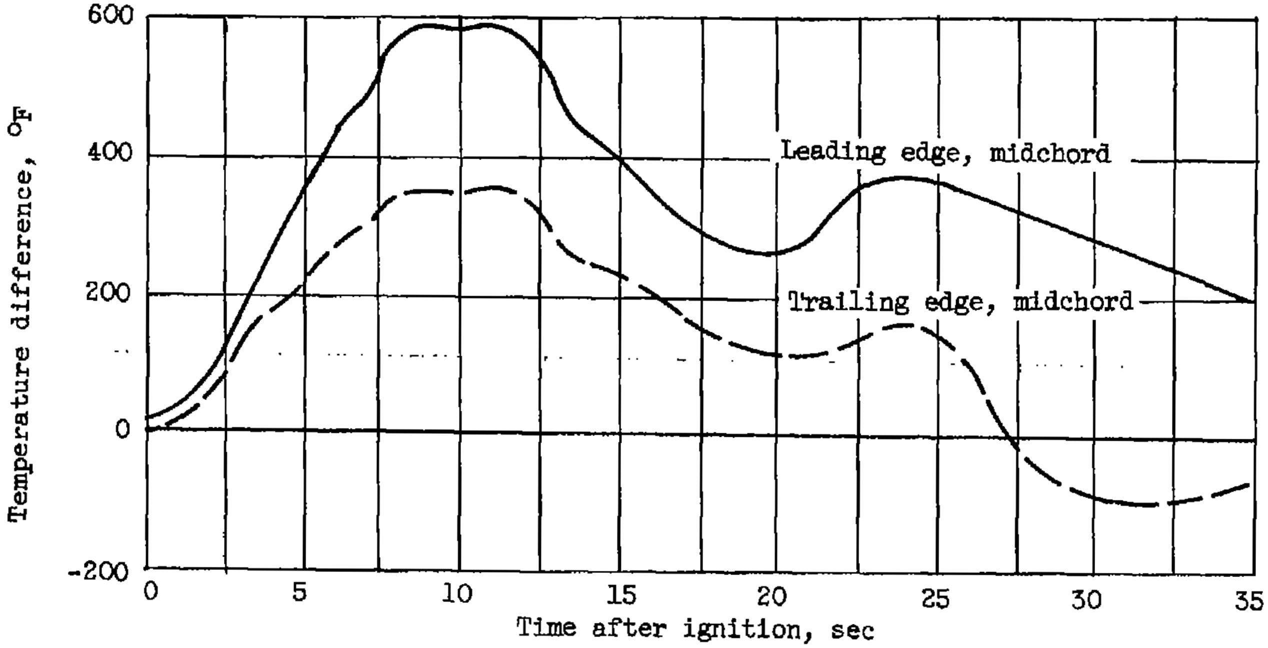
(b) Nozzle guide vane.

Figure 18. - Concluded. Transient temperatures during hot start.



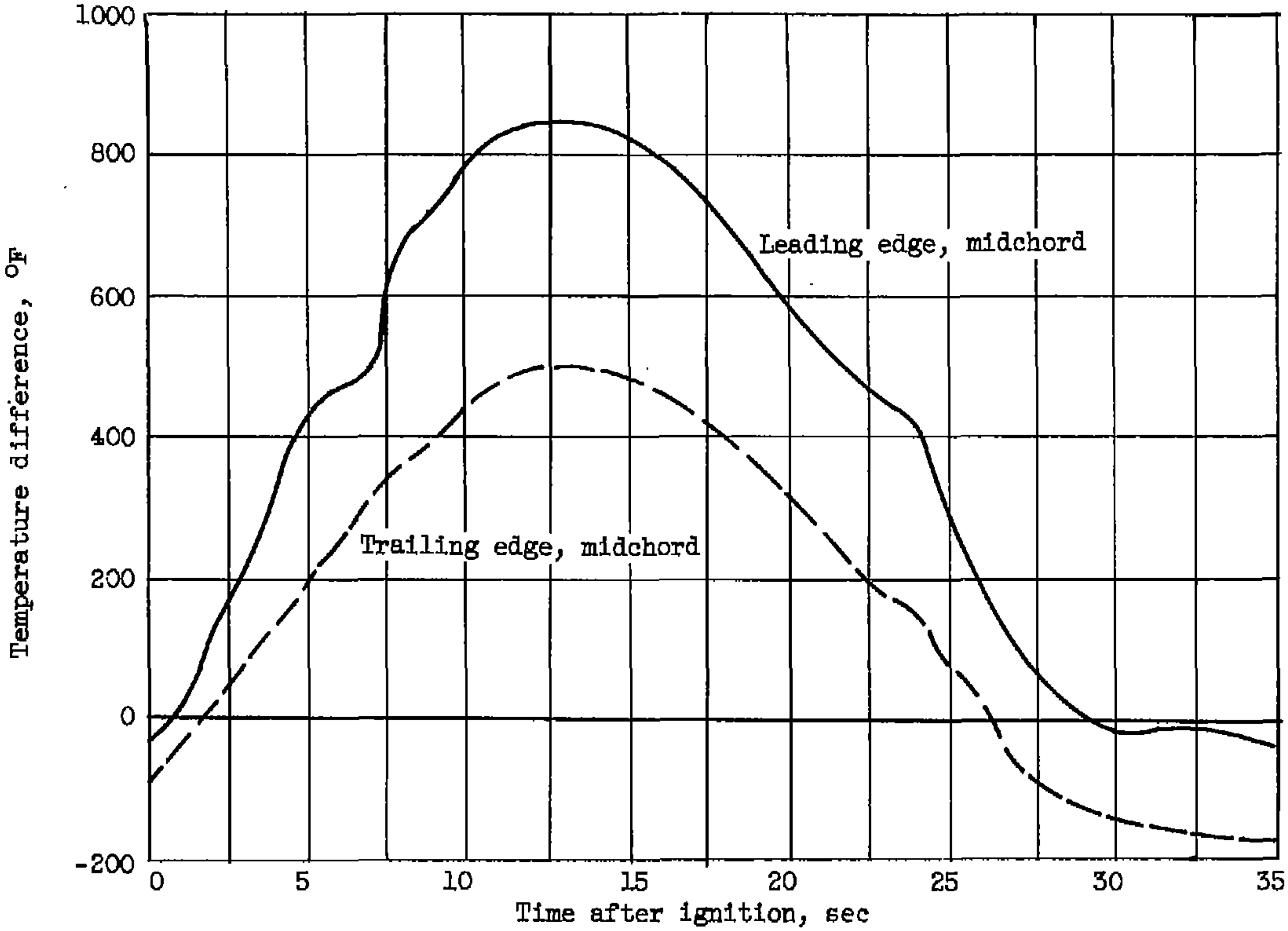
(a) Acceleration, 3000 to 7950 rpm.

Figure 19. - Turbine-blade temperature difference during transient runs.



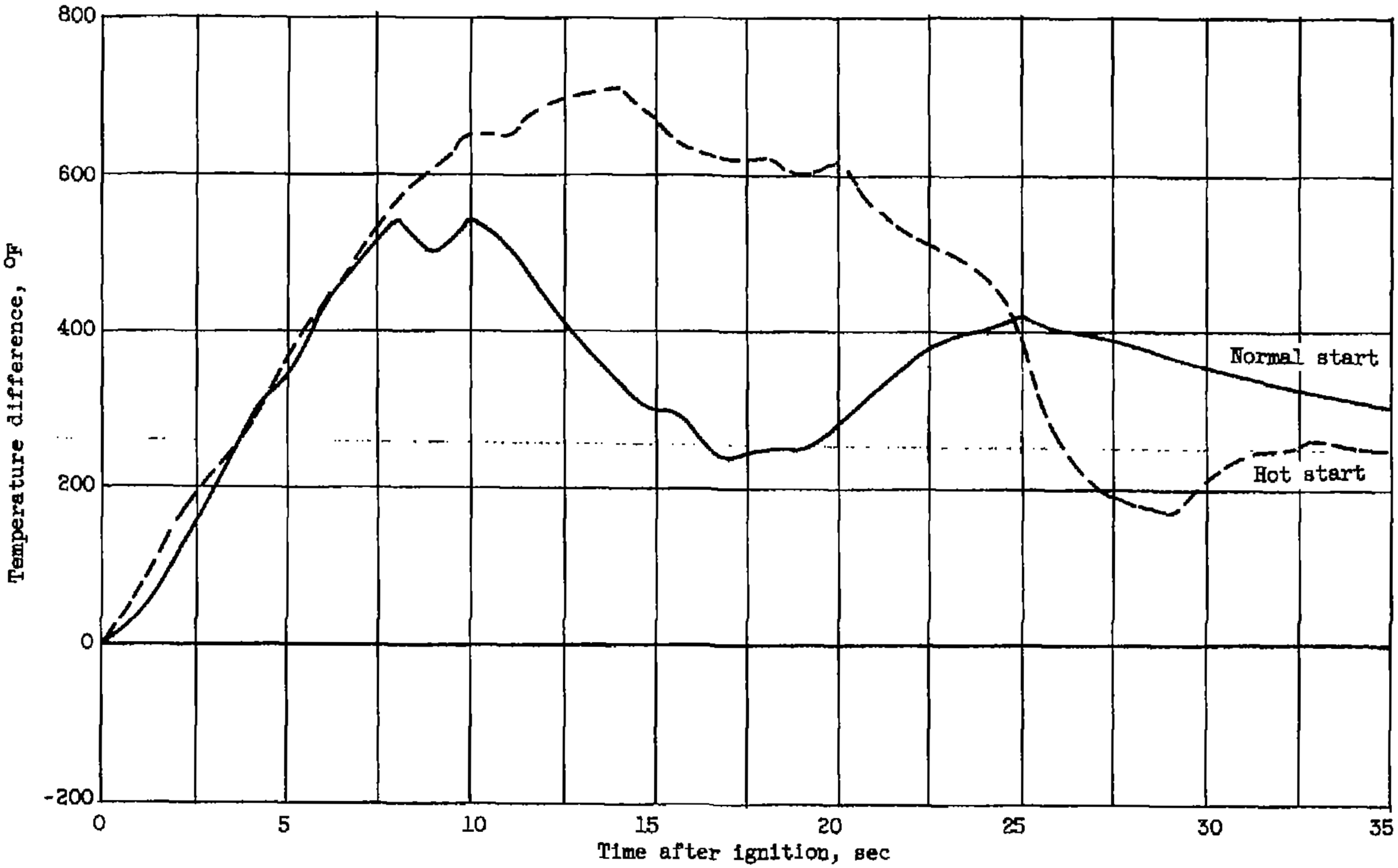
(b) Normal start.

Figure 19. - Continued. Turbine-blade temperature difference during transient runs.



(c) Hot start.

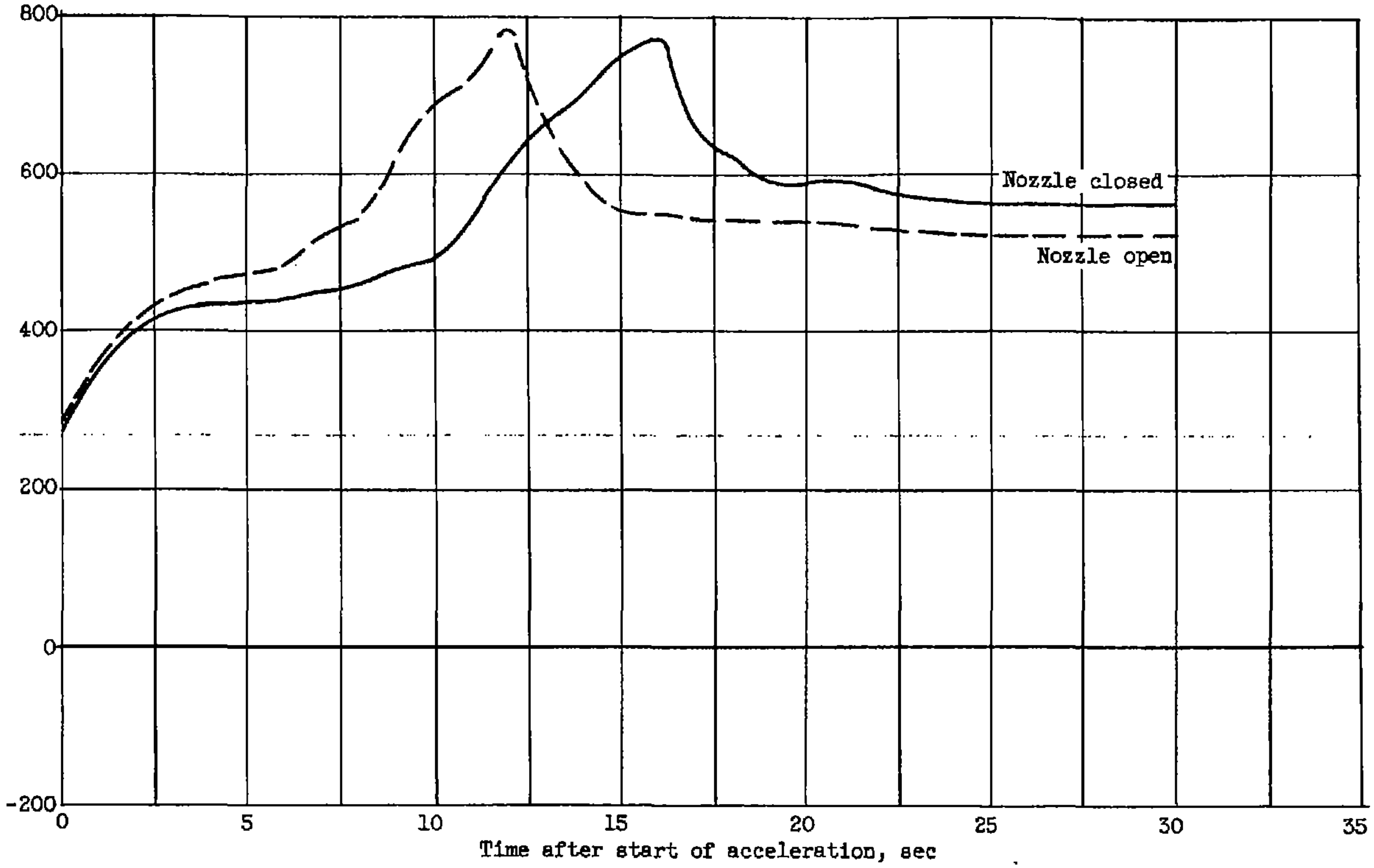
Figure 19. - Concluded. Turbine-blade temperature difference during transient runs.



(a) Normal and hot starts.

Figure 20. - Temperature difference measured between nozzle-guide-vane trailing edge and 3/4 chord at various operating conditions.

[redacted]



(b) Acceleration with open and closed nozzle settings at steady state.

Figure 20. - Concluded. Temperature difference measured between nozzle-guide-vane trailing edge and 3/4 chord at various operating conditions.

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[redacted]